AD-A088 551 OKLAHOMA STATE UNIV STILLWATER FLUID POWER RESEARCH --ETC F/G 13/3
SECOND GENERATION LOAD STABILITY SENSOR DEVICE.(U)
MAY 80 E C FITCH, R L DECKER, M T YOKLEY DAAK70-78-C-0067

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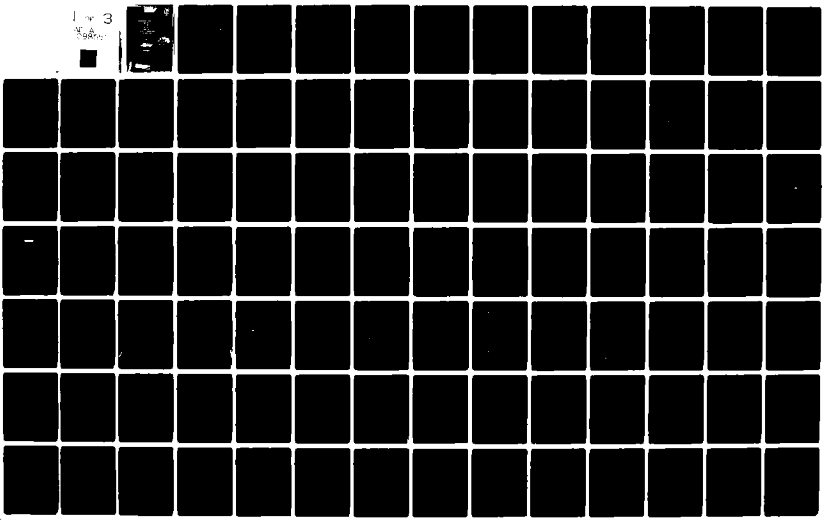

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M. T. / Yokley K. / Stokes D. / Shipley

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO. AD-A088 557

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
(6) Second Generation Load Stability Sensor Device

5. TYPE OF REPORT & PERIOD COVERED
May, 1978 to May 1980
Final

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Staff of the Fluid Power Research Center

8. CONTRACT OR GRANT NUMBER(s)
(15) DAAK70-78-C-0067

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Fluid Power Research Center
Oklahoma State University
Stillwater, OK 74074
(12) 226

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
(9) Final rept. May 78 - May 80

11. CONTROLLING OFFICE NAME AND ADDRESS
U.S. Army Mobility Equipment, Research and Development Command, Procurement and Production Office, Fort Belvoir, VA 22060

12. REPORT DATE
(11) May 80

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
ONRRP, Room 582 Federal Bldg.
300 East 8th Street
Austin, TX 78701

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Material Handling Equipment
Safety
Stability
Control

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
(over)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified 407263
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ABSTRACT

A previous study investigated the feasibility of a device to monitor the stability of material handling equipment (MHE). A mathmatical description of stability--known as a Stability Index--was developed. A methodology for determinining the Stability Index on conventional counterbalance lift trucks was devised. In addition an exploratory system was fabricated for demonstration and examination of the concept. It was found that a microcomputer-based device for monitoring stability on these vehicles is feasible.

This study attempts to refine the concept. The mathmatical theory was expanded to incorporate non-horizontal surfaces. The relative importance of the various terms was examined via sensitivity analysis techniques. A new microcomputer-based device which implements this new theory was designed, fabricated and tested. A test program was conducted to verify correct operation and to validate the concept.

SUMMARY

Numerous serious accidents occur every year when lift trucks are allowed to exceed safe operating attitudes and tip over. This often results in vehicle and load damage as well as injury to personnel. This report details the theory, design, and testing of a second generation Load Stability Sensor Device which provides a warning to the operator of any impending load instability which could result in an accident.

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PREFACE

This report is the Final Technical Report for the Second Generation Load Stability Sensor Device project, contract DAAK70-78-C-0067. This report documents both the theoretical procedures and also the microcomputer-based sensor device developed.

This study was conducted by the staff of the Fluid Power Research Center, Oklahoma State University, directed By Dr. E.C. Fitch, Jr., Mr. Robert L. Decker was Program Manager and Mr. M.T. Yokley Project Engineer.

Project Personnel contributing major efforts to the project were:

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P. Quinnett
D. Shipley

In addition, various members of the Fluid Power Research staff contributed to this study.

The Contract Officer Technical Representatives for this contract were:

Ms. Clair Orth
Mr. Jim Knaell
Mr. Emil Czul
Mr. Eugene Rodrick

The contract was monitored by the U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia.

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CHAPTER I

Introduction

Material handling equipment is a generic term which describes a multitude of mobile machines used for moving and stacking materials of all kinds. Included in this classification is not only conventional warehouse lift trucks and rough terrain lift trucks but also many other machines such as container handlers, cranes, and derricks. Industrial utilization of these machines has often placed constraint on design criteria--such as minimizing the vehicle wheel base in order to minimize aisle space in warehouses. Such constraints when coupled with the requirement to handle increasingly heavier loads at increasingly higher heights results in many of these devices being highly susceptible to accidents.

Certainly, accidents do occur. A recent study of 143 serious accidents (accidents for which the medical and disability benefits exceeded $7500.00) reveal that almost 30% of the accidents (in this sample) occured with operators with less than 6 months experience. Almost 60% of the accidents involved operators with less than 5 years experience. This study further showed that the vast majority of these accidents were directly attributable to the operator. This study concludes that experience is a good teacher but it takes too long to be effective. It further states that more effective training is needed.

The total cost of the 143 accidents studied was 2.2 million dollars [1].

The machines commonly operated by the military community are often of very similar design to that of industrial type machines. Therefore, many of the safety problems encountered in industrial operation are also significant problems with military operation. But, the military operation is unique in several respects. First, operators with very little experience will be commonly operating the vehicle. Second, the environment which the vehicle is operated may, because of the situation, be different than for which the vehicle was designed. Third, little time may be available for proper safety planning and preparing handling routes. Thus, the equipment design, in particular the design of safer equipment, is of special importance in military operation.

Although the design of equipment which is inherently safer, certainly is desirable, previously mentioned constraints often result in contradictory design requirements. For example, an increase in vehicle wheel-base and vehicle width will necessarily result in increased aisle spacing in warehouses. With warehouse space at a premium, such a change may be prohibitively expensive and deemed unacceptable. Because of this, devices which augment the operator's judgment and skill and can be retrofitted to existing vehicle designs are highly desirable. Although it may not be realistic to achieve such a device which totally elimi-

A system was proposed which utilizes a microcomputer to acquire the necessary vehicle information, compute intermediate vehicle loading parameters, and calculate a prediction of vehicle relative stability. A microcomputer-based exploratory system was designed and fabricated to demonstrate the feasibility of such a device. This exploratory system was designed to provide a go/no go indication of stability with a vehicle operating on a level surface under static conditions. A testing program was conducted which consisted of applying static load to the vehicle. Both go/no go and relative stability where compared to the theoretically calculated vehicle stability and also the observed stability conditions. It was found that the device provided good accuracy in predicting the stability of the vehicle under the above stated operated conditions in all cases except under extremely excessive and unrealistic loading conditions. It was concluded from the study that the approach proposed was indeed feasible.

This study expands the Stability Index concept previously developed. The theoretical procedures are refined to incorporate operation on non-horizontal surfaces. A sensitivity analysis was performed to identify significant terms in the theoretical equations. In addition, a new microcomputer system was designed and fabricated to implement the newly-derived theoretical procedures. The system was designed to be used as an

nates MHE accidents, a device which prevents some percentage of accidents or lessens the danger of accidents certainly is of tremendous value.

A previous study examined various approaches for monitoring and controlling stability of MHE. As part of that study a simplified stability model of counterbalanced type vehicles was developed. In addition, a quantative measure of stability--a Stability Index--was also defined. This study also examined the feasibility of various concepts for monitoring vehicle stability.

It was found that a system which derives information from readily measured parameters on the vehicle and utilizes this information to predict stability, provided the most merit for the realization of a system which would prove to be adequate when evaluated under the real world constraints:

--Speed of reaction to a dangerous condition.

--Interference with normal vehicle operation.

--Probability of malfunction and potential effects.

--Interchangeability on several different vehicles.

--Ease of installation.

--Simplicity and durability.

--Size

--Ease of field maintenance.

--Cost

engineering tool, allowing for ease of change of vehicle and test parameters as well as display of key test data.

An abbreviated testing program was conducted to verify the operation of the microcomputer device.

This report discusses the theoretical procedures as developed during this study. The Stability Index concept is reviewed and the new theoretical procedures incorporating non-horizontal slopes are integrated into the analysis. The computational methodology, as implemented on the microcomputer is developed. The results of the sensitivity analysis is discussed. This report also documents the microcomputer hardware and software as well as the test program. The implementation of the Stability Index conc ·pt is discussed. The results of the sensitivity analysis are also discussed. This report also provides documentation of the microcomputer hardware and test program.

CHAPTER II

STABILITY THEORY

This chapter provides a theoretical development of the mathematical description of vehicle stability. A stability index is defined and a mathematical relationship is developed to quantitatively describe the relative stability of a vehicle.

The concepts developed in this chapter have evolved from the consideration and examination of warehouse-type counter-balance lift trucks (CBLT). The concepts developed within this chapter are directly applicable to other vehicles with an analogous type of configuration, that is, a fixed front axle and a rear axle pivoting in a vertical plane. For example, a rough terrain lift truck designed around a conventional articulated wheel loader can be accommodated with the following theory.

STABILITY OF COUNTER BALANCE TYPE VEHICLES

In very simple terms, the fundamental concept governing the design of a counter-balance-type vehicle is to provide sufficient vehicle moments to counter-balance the moment of the load to be moved by the material handling equipment. Specifically, the vehicle moment about any of the various axies of rotation must exceed the load moment about that axis. If the above is not true, the vehicle will enter unstable configuration by rotating about one of the axies of rotation.

A conventional warehouse lift truck (WLT) has several axis which vehicle rotation may occur in the event of an unstable configuration. Such a vehicle typically has a rear axle which pivots in a vertical plane. This enables the vehicle's four tires to be on a non-planer surface with the load still distributed to all four tires. Because of this pivoted rear axle, three axies of rotation become critical in the evaluation of vehicle stability. These are (referring to Fig. 2-1):

--A line connecting the center of the area of contact of the two front tires.

--A line connecting the center of the area of contact of the left front tire to the pivoting point on the rear axle.

--A line connecting the center of the area of contact of the right front tire to the pivot point on the rear axle.

Rotation about the first of the above axies is typically called a longitudinal instability whereas rotation about either of the other two axies is considered a lateral instability. Note that these three lines connect to form a triangle. This triangle was commonly known as the stability triangle.

Vehicle stability is often analyzed by projecting the weight vector associated with the combination of the vehicle and the load into the plane defined by the stability triangle. The point at which this vector intersects the plane will, of course, be depending on the weight of the vehicle, weight and position of load, and orientation of the vehicle. If the projection is inside the stability

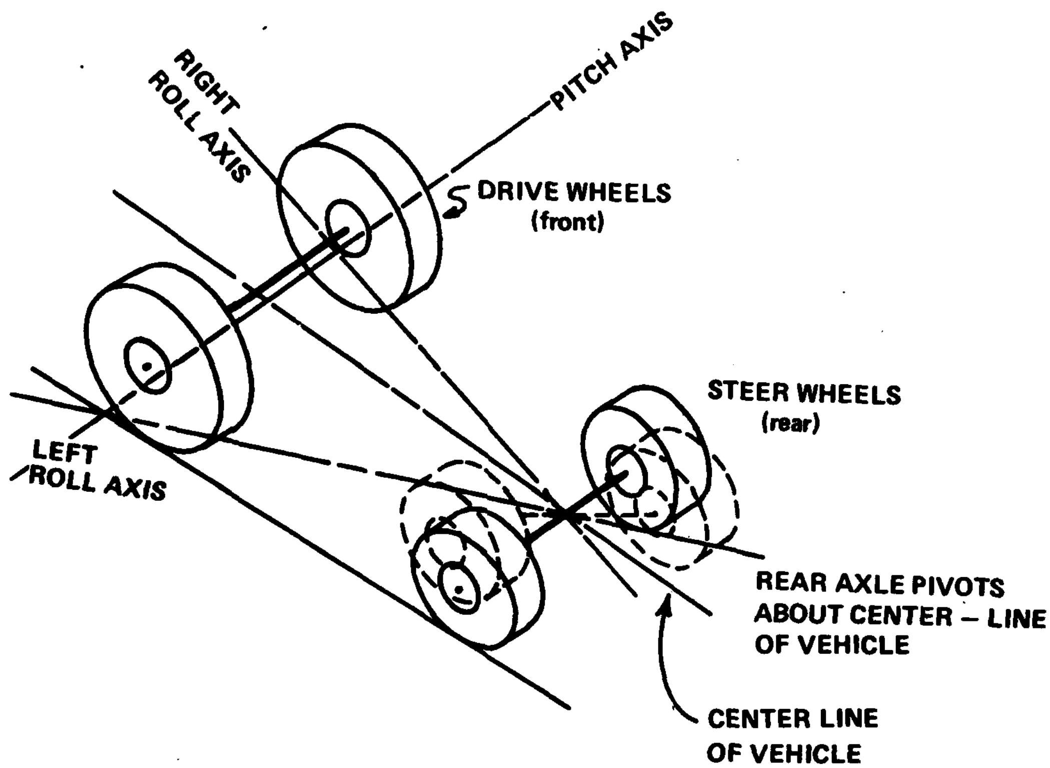


Fig. 2-1 Axes of Rotation for WLT

triangle then the vehicle is in a stable configuration. But, if this projection is outside the triangle then the vehicle is in an unstable configuration (this can easily be shown by a simple force balance considering the load force, reactions at the two front tires, and reaction at the pivot point on the rear axle).

QUANTIFYING STABILITY

The concept of relative stability is intuitively pleasing to one who has operated a vehicle such as a CLBT. An operator will sometimes notice a sensation of a "light rear-end" as he is traveling with a heavy load. Certainly this sensation is indeed indicative of reduced stability.

For the purpose of this study, relative stability will be related to the reaction forces at the points of support of the vehicle (where a reaction is a force applied to the vehicle point of support by the surface supporting it). In the case of a CLBT, these points of support are the four tires. For such a counterbalance-type vehicle, the reaction forces at the two rear tires are indicative of longitudinal stability (i.e., stability about the pitch axis). High reaction forces in these tires imply a stable configuration. As this force approaches zero, the vehicle is less and less stable about this axis. A zero force implies that the vehicle is balanced on the two front tires. It is physically impossible for the tires to sustain a negative reaction force.

Rotation about the left roll axis is constrained by the right front tire. Thus, in a similar manner, high reaction forces in this tire imply a highly stable configuration. As the reaction force approaches zero, the vehicle is less stable. A zero reaction force in the right front tire implies that the vehicle and load are balanced about the left roll axis. A negative reaction force in this tire is physically impossible. In a similar manner, the left front tire constrains rotation about the right roll axis.

Stability will be quantified by defining a stability index, $\overline{S}$, which is the moment caused by the restraining reaction force about each of the three axis of rotation. The stability index for a CBLT is a three component vector as shown in Equation 2-1.

$$\overline{S} = \begin{bmatrix} S_{PITCH} \\ S_{LR} \\ S_{RR} \end{bmatrix} = \begin{bmatrix} \text{-Moment about the pitch axis caused by reaction in rear supports} \\ \text{-Moment about the left roll axis caused by reaction in the right point of support} \\ \text{Moment about the right roll axis caused by reaction in the left point of support} \end{bmatrix} \quad (2\text{-}1)$$

Note that each of the components of $\overline{S}$ is indicative of stability about one of the axis of rotation. The sign notation was selected such that each term is non-negative--a negative component would imply that a force applied to the point of support (tire) is required which must hold it to the supporting surface which is physically impossible. A small value of any of the components implies low relative stability about the respective axis.

The definition of the stability index may be further generalized for vehicles which have more than three axis of rotation by incorpor-

ating additional components in the definition for $\overline{S}$.

Consider a typical CLBT configuration as shown in Fig. 2-2. Define a vehicle-based coordinate system as indicated. The four reactions ($\overline{R}_1$, $\overline{R}_2$, $\overline{R}_3$, $\overline{R}_4$) are applied <u>to</u> the vehicle and are located at $\overline{P}_1$, $\overline{P}_2$, $\overline{P}_3$, and $\overline{P}_4$, respectively. The S.I. may be mathematically defined as shown in Equation 2-2.

$$\overline{S} = \begin{bmatrix} S_{PITCH} \\ S_{LR} \\ S_{RR} \end{bmatrix} = \begin{bmatrix} -\lambda_{pitch} \cdot (\overline{P}_{R3} \times \overline{R}_3 + \overline{P}_{R4} \times \overline{R}_4) \\ -\lambda_{LR} \cdot (\overline{P}_{R2} \times \overline{R}_2) \\ \lambda_{RR} \cdot (\overline{P}_{R2} \times \overline{R}_1) \end{bmatrix} \tag{2-2}$$

Where

$\overline{\lambda}_{Pitch}$ = Direction Cosine Describing the Pitch Axis.

$\overline{\lambda}_{LR}$ = Direction Cosine Describing the Left Roll Axis.

$\overline{\lambda}_{RR}$ = Direction Cosine Describing the Right Roll Axis.

Note the direction cosines are vectors of unit length defined in Equation 2-3.

$$\overline{\lambda} = \frac{\overline{P}_B - \overline{P}_A}{|\overline{P}_B - \overline{P}_A|} \tag{2-3}$$

Where

$\overline{P}_A$, $\overline{P}_B$ are arbitrary points on the pertinent axis.

It was shown in the previous study [2] that the Stability Index defined in Equation 2-2 can be related vehicle parameter as shown in Equation 2-4 (refer to Fig. 2-3).

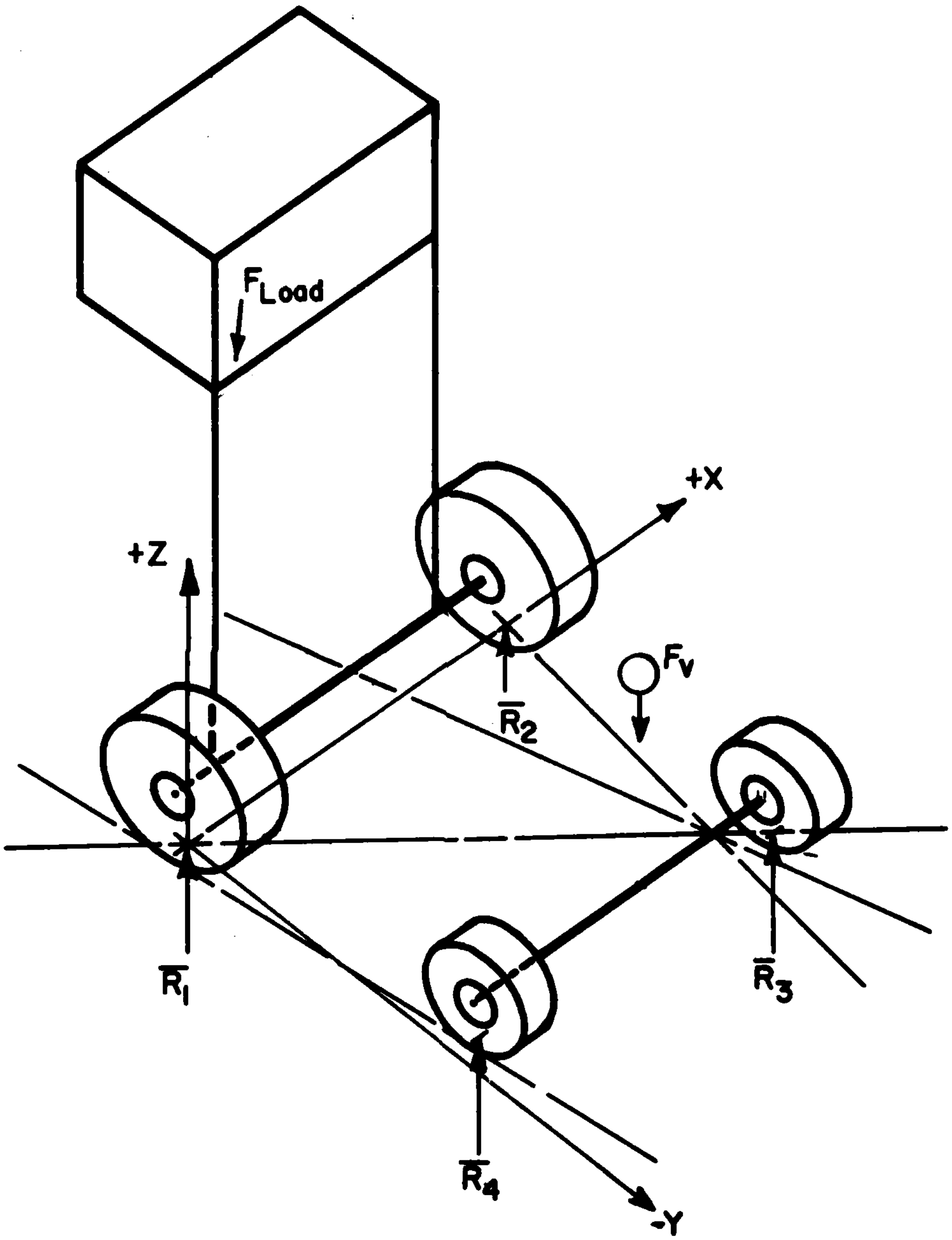


Fig. 2-2 Vehicle Reactions

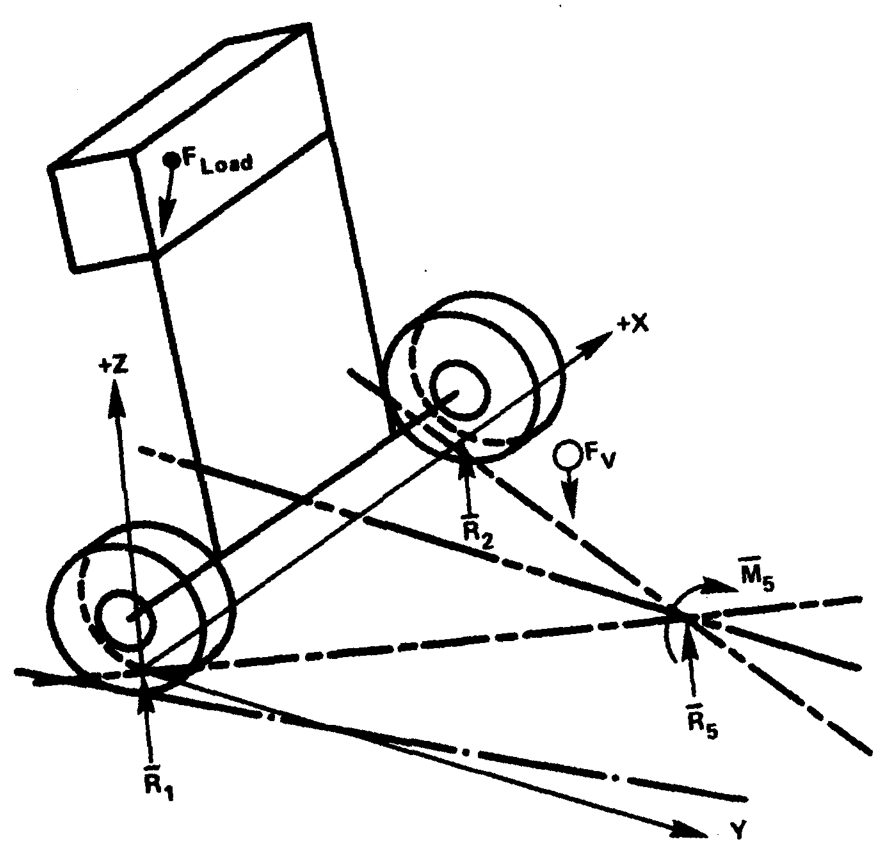


Fig. 2-3 Equivalent Vehicle Forces

$$\bar{S} = \begin{bmatrix} S_{PITCH} \\ S_{RR} \\ S_{LR} \end{bmatrix} = \begin{bmatrix} \bar{\lambda}_{PITCH} \cdot (\bar{P}_L \times \bar{F}_L + \bar{P}_V \times \bar{F}_V) \\ \bar{\lambda}_{LR} \cdot (\bar{P}_L \times \bar{F}_L + \bar{P}_V \times \bar{F}_V) \\ -\bar{\lambda}_{RR} [(\bar{P}_L \times \bar{F}_L + \bar{P}_V \times \bar{F}_V) - \bar{P}_{R2} \times (\bar{F}_L + \bar{F}_V) + \bar{\lambda}_{RR} \cdot \bar{M}_5)] \end{bmatrix} \qquad (2\text{-}4)$$

Where

$\bar{F}_L$ = Static and Dynamic Load Forces

$\bar{P}_L$ = Center of Gravity of Load

$\bar{F}_V$ = Static and Dynamic Vehicle Forces

$\bar{P}_V$ = Center of Gravity of Vehicle

Note that $\bar{M}_5$ is the moment applied to the pivot point by the rear axle. If this moment is zero or sufficiently small, then this equation can be rewritten as shown in Equation 2-5.

$$\bar{S} = \begin{bmatrix} \bar{\lambda}_{PITCH} \cdot (\bar{P}_L \times \bar{F}_L + \bar{P}_V \times \bar{F}_V) \\ \bar{\lambda}_{LR} \cdot (\bar{P}_L \times \bar{F}_L + \bar{P}_V \times \bar{F}_V) \\ -\bar{\lambda}_{RR} [(\bar{P}_L \times \bar{F}_L + \bar{P}_V \times \bar{F}_V) - \bar{P}_{R2} \times (\bar{F}_L + \bar{F}_V)] \end{bmatrix} \qquad (2\text{-}5)$$

By using the notation shown in Equation 2-6, this equation can be further simplified as shown in Equation 2-7.

$$\bar{M}_A^* = (\bar{P}_L - \bar{P}_A) \times \bar{F}_L + (\bar{P}_V - \bar{P}_A) \times \bar{F}_V \qquad (2\text{-}6)$$

IF $\bar{P}_A = \begin{vmatrix} 0 \\ 0 \\ 0 \end{vmatrix}$, then

$$\bar{M}_O^* = \bar{P}_L \times \bar{F}_L + \bar{P}_V \times \bar{F}_V \qquad (2\text{-}6a)$$

IF $\bar{P}_A = \bar{P}_{R2}$, then

$$\bar{M}^*_{P_{R2}} = (\bar{P}_L - \bar{P}_{R2}) \times \bar{F}_L + (\bar{P}_V - \bar{P}_{R2}) \times \bar{F}_V \tag{2-6b}$$

$$\bar{S} = \begin{bmatrix} \bar{\lambda}_{pitch} \cdot \bar{M}^*_o \\ \bar{\lambda}_{LR} \cdot \bar{M}^*_o \\ \bar{\lambda}_{RR} \cdot \bar{M}^*_o - \bar{P}_{R2} \times (\bar{F}_V + \bar{F}_L) \end{bmatrix} = \begin{vmatrix} \bar{\lambda}_{pitch} \cdot \bar{M}^*_o \\ \bar{\lambda}_{LR} \cdot \bar{M}^*_o \\ \bar{\lambda}_{RR} \cdot \bar{M}^*_{R2} \end{vmatrix} \tag{2-7}$$

It is important to understand that the physical interpretation of Equation 2-7 is that the stability index is the moment about each of the axis of rotation caused by the combination of the vehicle and load weight. Although it may not be readily apparent, the representation of $\bar{S}$ shown in Equation 2-7 is quite similar to the procedure of projecting the combination weight vector into the stability triangle and determining the distance this projection is located from each of the axis of rotation and finally calculating a moment using this distance and the appropriate components of the weight vector.

Thus far, the development of the quantification of stability has been quite general. Implicit in this development are the following assumptions:

1. A finite number of axis of rotation.
2. Moments about the rear axis pivot point (if any) are insignificant.

The quantification of stability as derived is mathematically very straight-forward. In practice, several complications do arise. These include:

--quantification of the load weight, and position (that is, position of the center of gravity).

--accurate measurement of dynamic forces.

--changes in vehicle configuration resulting from:

a. physical alteration to the vehicle, such as side extension.

b. tire deflection on loaded vehicles.

The following discussion addresses the first two of these items. This discussion will consider the specific example of a warehouse CBLT with cushion tires. The third item will not be considered as a significant influence in this discussion.

CBLT STABILITY MONITORING

Consider a conventional warehouse CBLT operating on possible non-horizontal surfaces under both static and dynamic conditions. Figure 2-2 shows the configuration of this vehicle. Note that the location of the center of gravity of the load cannot be readily measured using conventional transducers. In addition, the static and dynamic forces associated with the load may be difficult to reliably measure in a field environment. In order to circumvent this problem, the previous study identified several parameters which <u>are</u> readily measured and related these to the required load position and forces by developing a force balance model on the mast assembly. This relationship is shown in Equation 2-8 (refer to Ref. [2] for the development of this question).

$$\overline{P}_L \times \overline{F}_L = (\overline{P}_M - \overline{P}_T) \times F_T + (1/2)\overline{P}_M \times \overline{F}_L - \overline{P}_D \times \Delta\overline{F}_M \qquad (2\text{-}8)$$

Where

$\overline{P}_m = \overline{P}_{m_1} + \overline{P}_{m_2}$

$\overline{P}_{m_1}$ = Left Point of Attachment of Mast to Vehicle

$\overline{P}_{m_2}$ = Right Point of Attachment of Mast to Vehicle

$\overline{P}_T = \overline{P}_{T_1} + P_{T_2}$

$\overline{P}_{T_1}$ = Left Point of Attachment of Tilt Cylinder to Vehicle

$\overline{P}_{T_2}$ = Right Point of Attachment of Tilt Cylinder to Vehicle

$\overline{F}_T = \overline{F}_{T_1} = \overline{F}_{T_2}$

$\overline{F}_{T_1}$ = Force in Left Tilt Cylinder

$\overline{F}_{T_2}$ = Force in Right Tilt Cylinder

$\overline{F}_L$ = Force in the Lift Cylinder

$\overline{P}_D = \overline{P}_{m_2} - \overline{P}_{m_1}$

$\Delta\overline{F}_m = (\overline{F}_{m_2} - \overline{F}_{m_1})/2$

$\overline{F}_{m_1}$ = Force Applied to Mast by the Vehicle at the Left Point of Attachment ($\overline{P}_{m_1}$)

$\overline{F}_{m_2}$ = Force Applied to Mast by the Vehicle at the Right Point of Attachment

Eq. 2-8 can then be used with Eq. 2-6a and 2-7 to calculate the S.I. Utilization of these equations require the quantization of the following information:

- -- Force in tilt cylinders.
- -- Orientation of tilt cylinders.
- -- Dynamic and static load forces.
- -- Dynamic and static forces transmitted from the axle to the mast.
- -- Dynamic and static vehicle forces.
- -- Orientation of vehicle.

If these are known, then these equations can be used to quantify stability. The monitoring of stability real time on a machine in normal operation will require appropriate sensors to determine the above information.

Note that the development thus far is consistent with the results obtained in Ref. [2]. Eq. 2-8 and 2-7 are, in fact, the results previously obtained. The following discussion explores the impact on non-level surfaces and dynamics forces on the utilization of the S.I. theory. In addition, the specific measurement methodology necessary for field application of this theory is addressed.

FIELD APPLICATION - DYNAMIC CASE

Consider the operation of a CBLT on non-horizontal surfaces under dynamic conditions. The application of Eq. 2-8 and 2-7 in this situation requires a detailed analysis of the individual terms

in these equations as follows:

$\overline{F}_L$, $\overline{F}_V$ -- These forces can be represented with both static and dynamic components as shown in Equations 2-9a to 2-9b.

$$\overline{F}_V = \overline{F}_{VS} + \overline{F}_{VD} \tag{2-9a}$$

$$\overline{F}_L = \overline{F}_{LS} + \overline{F}_{LD} \tag{2-9b}$$

where the subscripts S and D represent static and dynamic, respectively.

The load and vehicle forces may be also represented as shown in Equation 2-10a and 2-10b.

$$\overline{F}_V = M_V\overline{g} + M_V\overline{a}_V = M_V(\overline{g} + \overline{a}_V) \tag{2-10a}$$

$$\overline{F}_L = M_L\overline{g} + M_L\overline{a}_L = M_L(\overline{g} + \overline{a}_L) \tag{2-10b}$$

where

M_V = Mass of Vehicle

M_L = Mass of Load

$\overline{g}$ = Acceleration Due to Gravity

$\overline{a}_V$ = Vehicle Acceleration

$\overline{a}_L$ = Load Acceleration

Since the vehicle-based coordinate system may rotate relative to a gravitational reference, the direction of the vector $\overline{g}$ is a function of the orientation of the vehicle. This can be represented as shown in Equation 2-11.

$$g = |\overline{g}|\lambda_g \tag{2-11}$$

Where

$|\bar{g}|$ = Magnitude of $\bar{g}$

$\bar{\lambda}_g$ = Direction cosine which maps $|\bar{g}|$ into the vehicle-base coordinate system.

Equation 2-11 and 2-12 can be substituted into Equation 2-10a and 2-10b to obtain Equations 2-13a and 2-13b.

$$\bar{M}g = M\,|\bar{g}|\,\bar{\lambda}g = W\bar{\lambda}_g \tag{2-12}$$

$$\bar{F}_V = M_V\bar{\lambda}g + W_V\bar{a}_V/(|\bar{g}|) \tag{2-13a}$$

$$\bar{F}_L = W_L\bar{\lambda}g + W_L\bar{a}_L/(|\bar{g}|) \tag{2-13b}$$

Where

W = Weight

W_V = Weight of the Vehicle

W_L = Weight of the Load

Equation 2-13a and 2-13b require the quantification of several terms--W_L, W_V, $\bar{\lambda}g$, $\bar{a}_V$, and $\bar{a}_L$. Of these, the terms W_V and M_V are constant and known for a specific vehicle. The direction cosine $\bar{\lambda}_g$ can be readily determined by measuring the orientation of the vehicle by simple gravitational-referenced transducer such as pendulum-type angle sensor or gyroscopic devices. This term can then be determined as shown in Equation 2-14

$$\bar{\lambda}_g = \begin{bmatrix} \sin\theta_y \\ \sin\theta_x \\ -\sqrt{1-\sin^2\theta_x-\sin^2\theta_y} \end{bmatrix} \tag{2-14}$$

where θ_x and θ_y are defined as angle of rotation about the X and Y axes, respectively, with rotation towards the position direction denoted as a positive rotation.

The acceleration terms $\bar{a}_L$ and $\bar{a}_V$ may be determined directly from accelerameter transducers. Several factors must be considered if this approach is to be utilized including:

-- Ruggedness of accelerameters.

-- Cost of the devices.

-- Added complexity.

-- Speed of reaction.

Note that the first three of the factors for the most part are a result of the present state-of-the-art of these type of transducers and associated signal conditioning. Although the delicate nature and relatively high cost of these devices are significant concerns at this time, it is reasonable to assume that technological advancements in the near future may diminish such concerns.

But this discussion of the suitability of accelerameter-type devices is really of academic interest only because the last factor--speed of reaction--is a fundamental problem. Consider for a moment the situation where a CBLT is being operated at a high speed and the operator initiates a sharp turn. By the time the lateral acceleration is detected and the operator is warned, there would not be sufficient reaction time for the operator to correct the situation and avoid such an accident. Thus, in very simplistic terms, this information may serve little more than to "inform the operator the

vehicle has overturned." This point will be discussed in further detail later in this report.

The remaining term in Equation 2-13b to be determined is the weight of the load, W_L. Because the load must be raised and lowered relative to the mast assembly, installing sensors in, say, the forks will be extremely difficult because of the problem of connecting these via cables for monitoring the transducer signal. An approach to determining an indication of the load weight is to determine the force in the lift cylinder. The force is the component of both the static and dynamic load forces parallel to the lift cylinder. Under normal loading conditions, the static portion of $\overline{F}_L$ is a result of only the weight of the load (and the weight of the portion of the mast which elevates). Since the orientation of the vehicle and thus the direction of the load "weight" force is known, the weight can be related to the static (average) component of F_{Lift} as shown in Equation 2-15.

$$W_L = \frac{f_{lift}}{\sqrt{1 - \sin^2(\theta_x + \theta_M) - \sin^2\theta_y}} \qquad (2\text{-}15)$$

Where

θ_m = Mast angle relative to X-Y plane
(forward tilt is a positive angle.

(Note-For this discussion, the load will be defined to consist of the payload plus the weight of the mast. The weight of the portion of mast which is elevated--W_{mm}--is reflected in the lift cylinder pressure. The weight of the stationary portion of the mast--W_{ms}--

is a constant and can be accounted for in calculations as appropriate.) W_L can then be used as required in Equation 2-13b and 2-7.

This approach results in a suitable indication of W_L by determining the lift cylinder force. A convenient means of determining F_{Lift} is by measuring the lift cylinder pressure and relating this to F_{Lift} by the cylinder area. Two problems are encountered with this approach. First, some CBLT's use compound cylinders where the effective area is a function of the cylinder height. Second, when the mast encounters mechanical stops at its maximum height, erroneous information (high values for W_L) may be inferred.

$\bar{F}_T$--The force in the tilt cylinder, $\bar{F}_T$, can be determined (for both static and dynamic conditions) by measuring the pressure in both sides of the tilt cylinders and combining them as shown in Equation 2-16.

$$F_T = P_1A_1 - P_2A_2 \tag{2-16}$$

Where

F_T = Magnitude of combined force of the two tilt cylinders

P_1 = Pressure on the rod side of the tilt cylinder

P_2 = Pressure on the head side of the tilt cylinder

A_1 = Combined area of the rod side of the two tilt cylinders

A_2 = Combined area of the head side of the two tilt cylinders

The vector $\bar{F}_T$ can be described as shown in Equation 2-17.

$$\bar{F}_T = \begin{bmatrix} F_{Tx} \\ F_{Ty} \\ F_{Tz} \end{bmatrix} = F_T \begin{bmatrix} O \\ \mathrm{Cos}\ \theta_T \\ \mathrm{Sin}\ \theta_T \end{bmatrix} \tag{2-17}$$

θ_T = Angle the tilt cylinder forms with the X-Y plane

The X component is equal to zero because it is assumed that there is no side loading on the tilt cylinders.

Note that measuring the tilt cylinder pressures provides a good indication of $\overline{F_T}$ (both in static and dynamic conditions) with one very significant exception. If the cylinders are designed such that their travel is limited by mechanical stops, then pressure may be trapped in the cylinder which is not indicative of F_T. This is not a problem with vehicles which utilize tilt cylinders with hydraulic stops. Unfortunately, few vehicles utilize such cylinders.

ΔF_m--The last term in Eq. 2-8 which must be discussed is $\overline{\Delta F_m}$. This term relates the force imbalance in the two points of attachment of the mast to the axle. The term was specifically derived to determine forces which cause "side" loading on the mast.

Interestingly, the term $\overline{P_D} \times \overline{\Delta F_m}$ is the moment about the centerpoint on the front axle caused by load forces which tend to rotate the mast about this point and are resisted by the force $\overline{\Delta F_m}$. Eq. 2-18 expands this term. Note that the Y and Z components of $\overline{P_D}$ are a result of the vehicle geometry.

The force $\overline{\Delta F_m}$ can originate from two sources--side loading caused by off-center loads or operation on non-horizontal surfaces and loads parallel to the Y-axis applied directly to the mast assembly. The later situation is considered to be a very unusual loading of the vehicle and is not considered a major influence. This study only

considers the form situation--side loading. Thus, the composite term $\overline{m_{cp}}$ is a measure of side loading.

If the mast is modeled as a simple cantilevered beam (cantilevered at the axle), then the stresses in the side of the mast are directly related to $\overline{m_{cp}}$. Therefore, measurement of this stress--using strain guages--will provide an indication of the desired information, that is, the side loading. The application of this is shown in Eq. 2-19.

$$\bar{P}_D \times \overline{\Delta F_m} = \begin{bmatrix} X_D \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} \Delta F_{mx} \\ \Delta F_{my} \\ \Delta F_{mz} \end{bmatrix} = \begin{bmatrix} 0 \\ -X_D \Delta F_{mz} \\ X_D \Delta F_{my} \end{bmatrix} = \begin{bmatrix} 0 \\ M_{cpy} \\ M_{cpz} \end{bmatrix} = \bar{M}_{cp} \tag{2-18}$$

$$\bar{M}_{cp} = k\epsilon \begin{bmatrix} 0 \\ \cos\theta_m \\ -\sin\theta_m \end{bmatrix} \tag{2-19}$$

Where

k = Emperically derived constant of proportionality

ε = Measured Strain

θ_m = Mast angle (as previously defined)

In order to determine a numeric value for $\overline{S}$, various constants and parameters which are related to the vehicle geometry, orientation, and loading must be specified. Parameters which are a function of load and orientation and which must be measured on a real-time basis include:

-- Vehicle orientation (2 directions)

-- Vehicle acceleration (3 directions)

-- Load acceleration (3 directions)

-- Tilt cylinder pressure (2 directions)

-- Lift cylinder pressure

— Mast angle

Note that all parameters are measured relative to the vehicle-based coordinate system previously defined.

In summary, Eq. 2-13a, 2-13b, 2-14, 2-15, 2-16, 2-17, and 2-19 can be combined with Eq. 2-8 and 2-7 to determine the Stability Index for dynamic operation on non-horizontal surfaces as shown in Eq. 2-20 (a through i).

FIELD APPLICATION-STATIC CASE

If only static forces are considered, then the acceleration terms, a_L and a_V, are equal to zero and Eq. 2-20c and 2-20d can be simplified as shown in Eq. 2-21a and 2-21b.

$$\bar{S} = \begin{bmatrix} \lambda_{pitch} \cdot \bar{M}_e \\ \lambda_{LR} \cdot \bar{M}_e \\ \bar{\lambda}_{RR} \cdot M_e - \bar{P}_{RE} x (\bar{F}_V + \bar{F}_L) \end{bmatrix} \tag{2-20a}$$

$$\bar{M}_e = \bar{P}_L x F_L + \bar{P}_V x F_V \tag{2-20b}$$

$$\bar{F}_V = W_V \bar{\lambda}_g + W_V \bar{a}_V / (|\bar{g}|) \tag{2-20c}$$

$$\bar{F}_L = W_L \bar{\lambda}_g + W_V \bar{a}_V / (|\bar{g}|) \tag{2-20d}$$

$$W_L = f_{Lift} / (\sqrt{1 - \sin^2(\theta_x + \theta_m) - \sin^2 \theta_y}) \tag{2-20e}$$

$$\bar{\lambda}_g = \begin{bmatrix} \sin \theta_y \\ \sin \theta_x \\ - \sqrt{1 - \sin^2 \theta_x - \sin^2 \theta_y} \end{bmatrix} \tag{2-20f}$$

$$F_T = P_1 A_1 - P_2 A_2 \tag{2-20g}$$

$$F_T = F_T \begin{bmatrix} 0 \\ \cos\theta_T \\ \sin\theta_T \end{bmatrix} \tag{2-20h}$$

$$\bar{P}_D \times \overline{\Delta F}_m = k\epsilon \begin{bmatrix} 0 \\ \cos\theta_m \\ -\sin\theta_m \end{bmatrix} \tag{2-20i}$$

$$\bar{F}_V = W_V \bar{\lambda}_e \tag{2-21a}$$

$$\bar{F}_L = W_L \bar{\lambda}_L \tag{2-21b}$$

This equation requires the real-time measurement of the following vehicle parameters:

-- Vehicle orientation (2 directions)

-- Tilt cylinder pressure (2 sides)

-- Lift cylinder pressure

-- Mast angle

Note by considering only static condition, the number of parameters which must be measured via transducers and appropriate signal conditioning has been reduced from 12 to 6.

FIELD IMPLEMENTATION

The equations previously defined for calculating the S.I. are suitable for the real-time implementation of a Stability Monitor for CBLT. A system could be designed using a low-cost microcomputer --perhaps using a single chip device. A block diagram for such a

monitor is shown in Fig. 2-4.

Note that the various parameters which describe the vehicle's loading, orientation, and dynamic conditions are converted to electrical signals by appropriate transducer. These electrical signals are then converted to a digital representation by the analog-to-digital converter for processing by the microcomputer. If it is determined that an unstable or potentially dangerous condition has been attained, an audible alarm is sounded and a visual indication is displayed to the operator identifying the axis about which the instability is occurring.

This hardware could be expanded to include the control function as shown in Fig. 2-5. Note that this system provides for diminished control authority as a function of the relative stability. The operation is as follows:

When the relative stability about any axis is less than a preset limit, the proportional valves in the tilt and lift circuits are partially closed by commands from the microcomputer. This reduces the flow rate, and thus the power capability to these circuits to reduce the capability to lift and tilt forward. As the relative stability is further reduced, the valves are further closed. The control authority is gradually reduced by reducing the power capabilities in these circuits until movement is completely inhibited.

Note that this circuit is configured such that the mast is allowed to be lowered or tilted backwards in order to move from the unstable configuration. It is possible that these may not be the

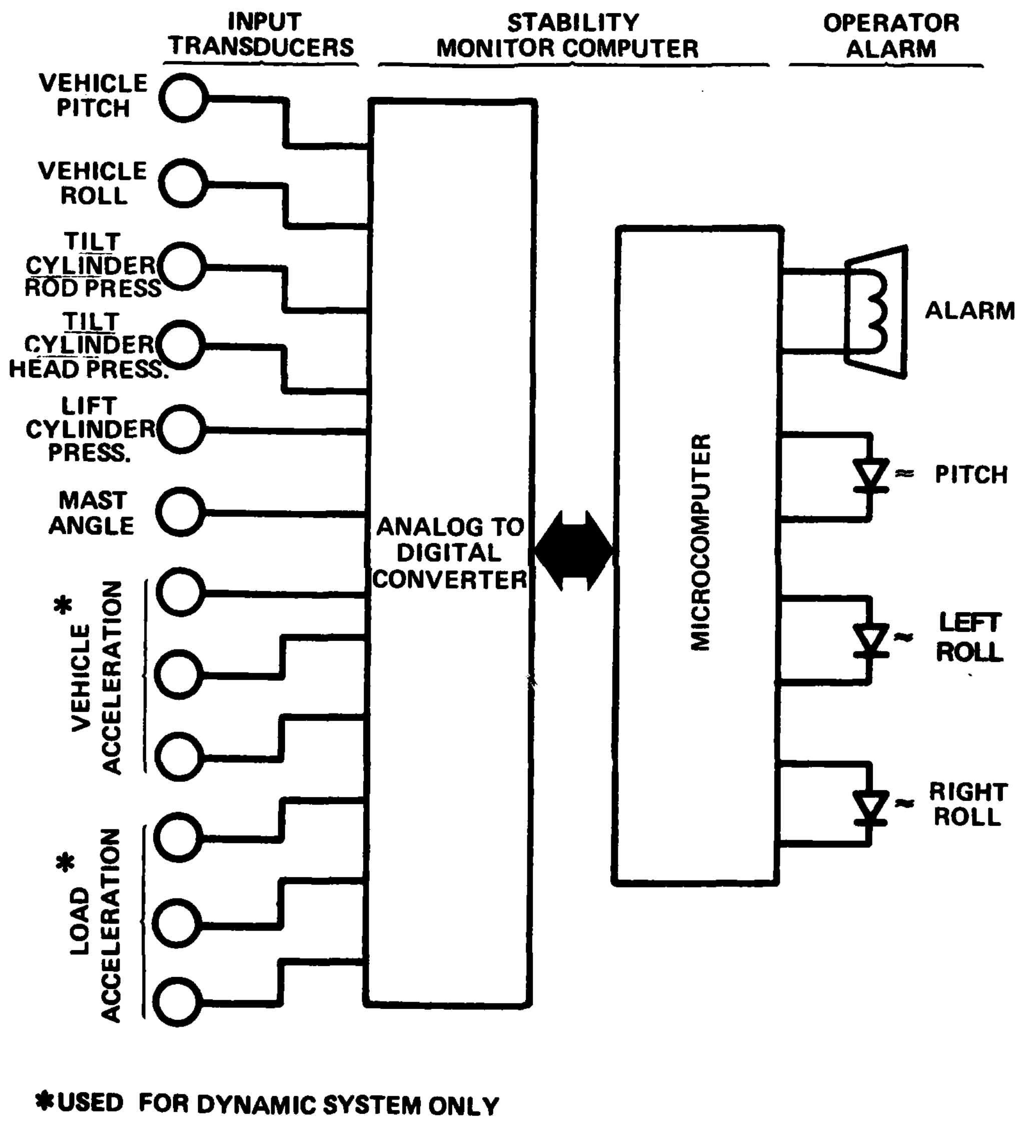
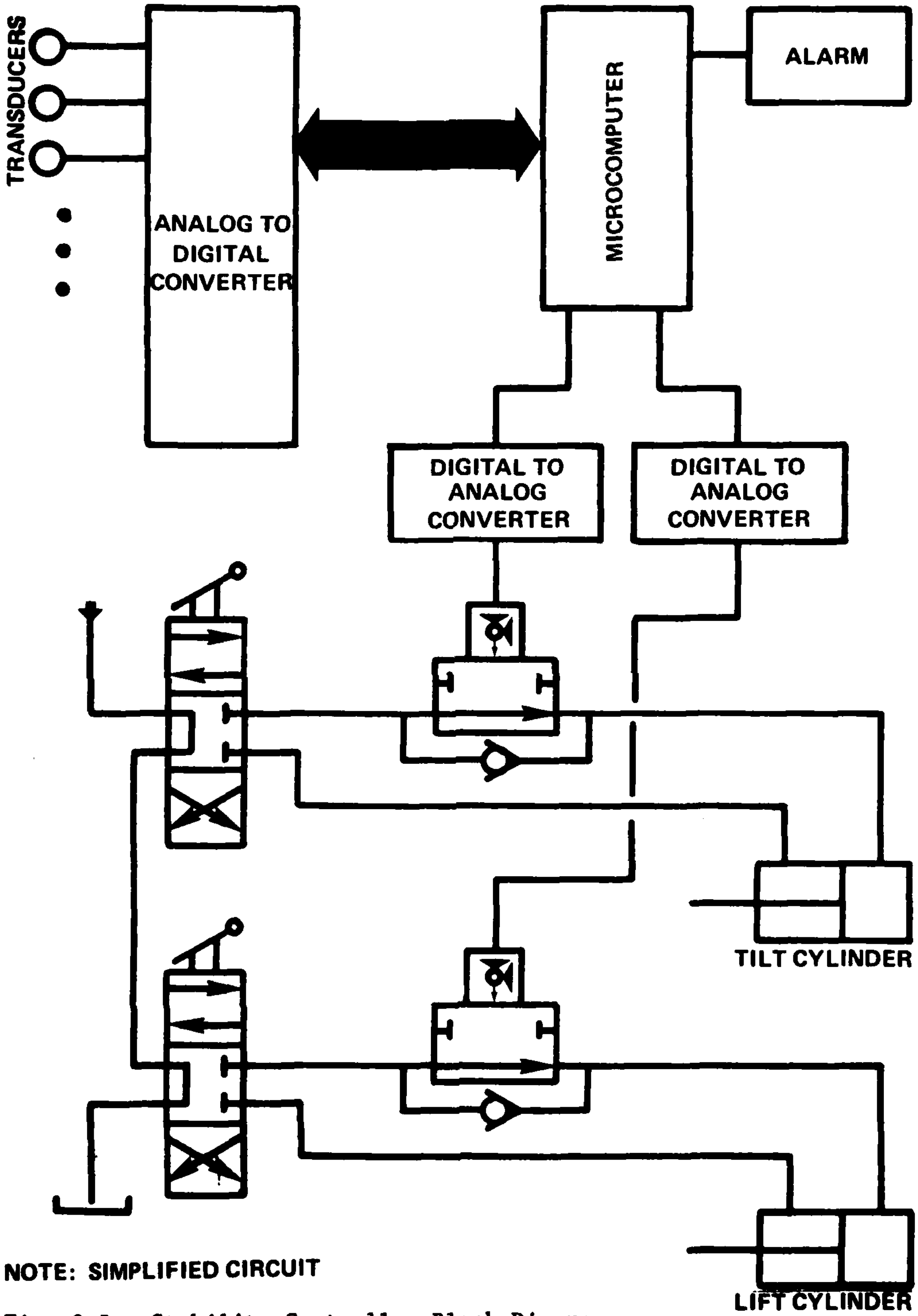


Fig. 2-4 Stability Monitor Block Diagram



NOTE: SIMPLIFIED CIRCUIT

Fig. 2-5 Stability Controller Block Diagram

appropriate actions. Such is the case when, say, on a side incline tilting the mast backwards, reduces the lateral stability. A more sophisticated system would augment the operator's commands to reduce control authority in the appropriate direction of each circuit by calculating the correct actions to be performed to lessen the instability (the methodology for this is beyond the scope of this study).

Fig. 2-6 and 2-7 show flowcharts for the systems depicted in Fig. 2-4 and 2-5 respectively.

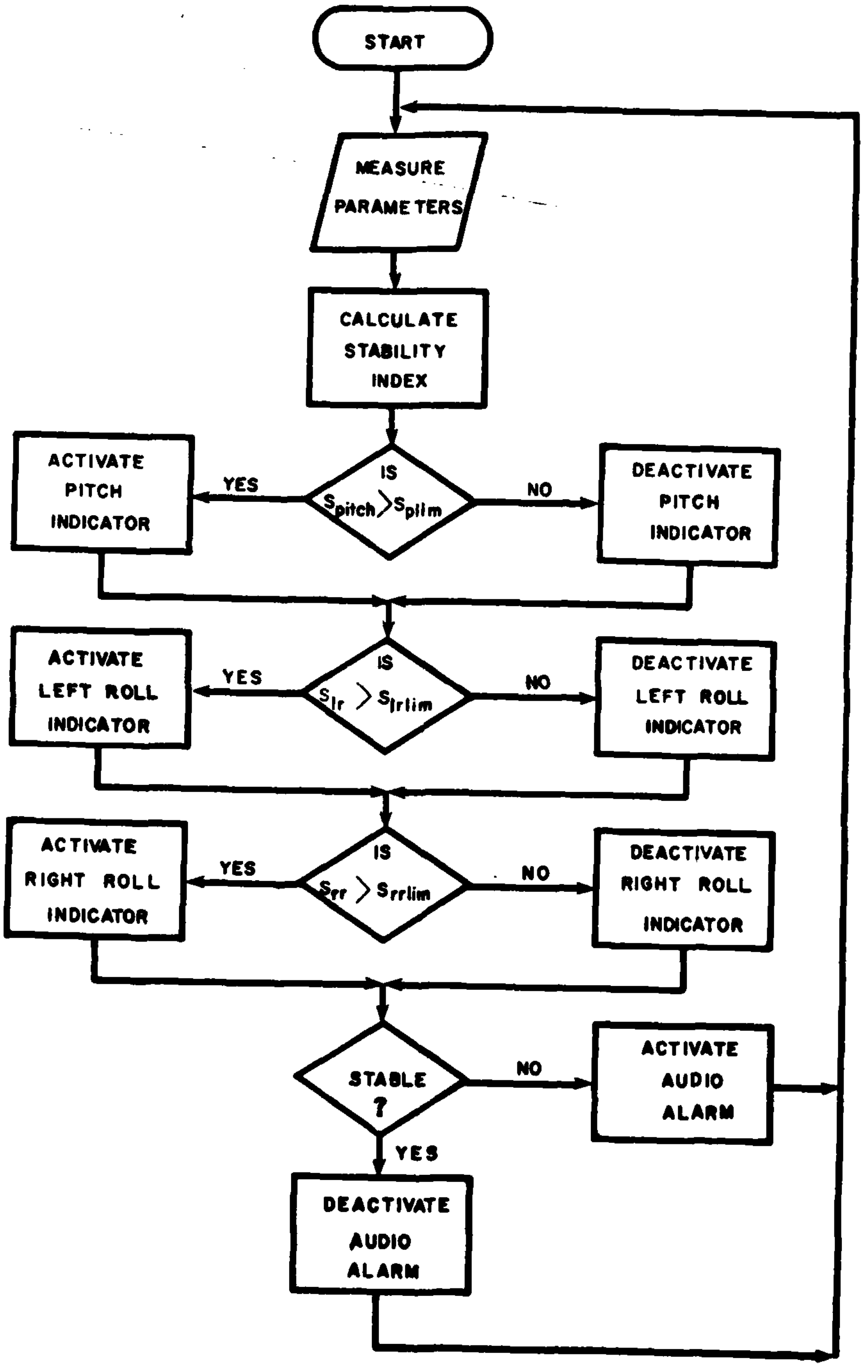


Fig. 2-6 Flowchart for Stability Monitor

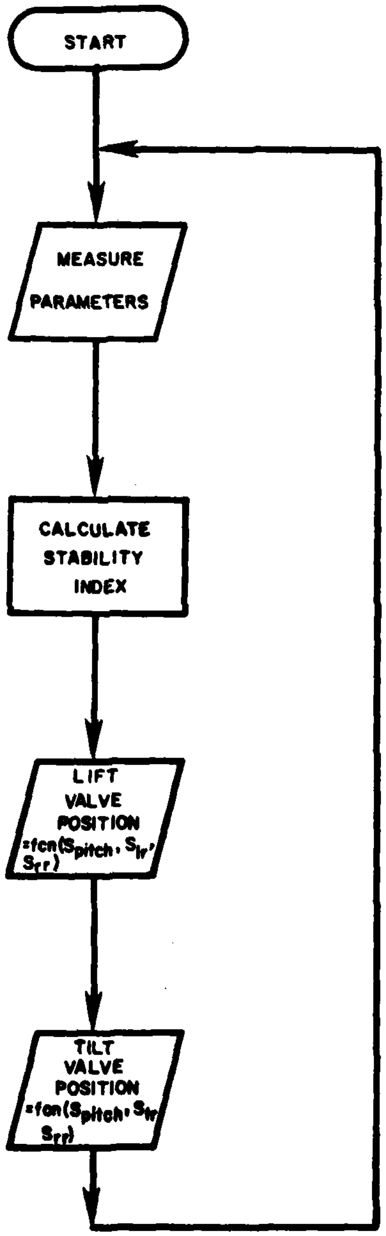


Fig. 2-7 Flowchart for Stability Controller

CHAPTER III

SENSITIVITY ANALYSIS

SENSITIVITY FUNCTIONS

Equations were developed in Chapter II which describe the stability of material handling equipment--in the form of a Stability Index--for material handling equipment in general. Equations were also developed to describe the stability of CBLT which required the measurement of several parameters and the specification of various constants. Although the complexity of the equations derived is not great, the fact that multiple parameters must be measured using some form of sensor introduces additional costs and complexity into the system. Certainly, if any of these parameters have little effect on the overall determination of vehicle stability, it would be highly desirable to eliminate these from the system.

This chapter examines the relative importance of the various terms of the Stability Index equations by performing a sensitivity analysis on these equations. The specific questions to be addressed are as follows:

--Which terms (if any) can be ignored?

--Which term(s) (if any) have a dominant effect on the overall determination of stability?

The technique employed is to develop a mathematical sensitivity

function which relates the percent change (percent of full scale) in Stability Index, to a percent change in a given term. When this sensitivity function is evaluated using suitable numeric values, the resulting magnitude is indicative of the "effect" a particular term has on the Stability Index. Note that values greater than one (in absolute magnitude) indicate a strong influence by a particular term. Similarly, values substantially less than one indicate little or no influence.

The sensitivity function is defined as shown in Eq. 3-1.

$$S_X^N = \frac{\delta N/N_{F.S.}}{\delta X/X} \tag{3-1}$$

where

S_X^N = Sensitivity of N with respect to X.

$N_{F.S.}$ = Full scale value of N.

Eq. 3-1 may be rewritten in a more convenient form as shown in Eq. 3-2.

$$S_X^N = \frac{X}{N} \frac{\delta N}{\delta X} \tag{3-2}$$

STABILITY INDEX SENSITIVITY FUNCTIONS

To assist in the development of the sensitivity functions for Stability Index (S.I.), the equations derived in Chapter 2

have been rewritten as shown in Eq. 3-3.

$$S_i = \overline{\Lambda}^i \cdot \left[P_V \times W_V + (\overline{P}_M - \overline{P}_T) \times \overline{F}_T + \frac{1}{2} \overline{P}_M \times \overline{\lambda}_g (W_L + W_{ms}) - \overline{M}_{CP} + \delta_{i3} \overline{P}_{R2} \times \overline{\lambda}_g (W_V + W_L) \right] \quad (3\text{-}3)$$

where:

$$\overline{\Lambda}^1 = \lambda_P, \overline{\Lambda}^2 = \overline{\lambda}_{LR}, \overline{\Lambda}^3 = \overline{\lambda}_{RR}$$

$$S_1 = S_P,\ S_2 = S_{LR},\ S_3 = S_{RR}$$

$$\delta_{i3} = \begin{cases} 0 & \text{if } i \neq 3 \\ 1 & \text{if } i = 3 \end{cases}$$

By using the identities in Appendix C, the various sensitivity function may be written by inspection. The following derives these functions for the S.I. with respect to W_V, W_L, W_{ms}, $\overline{P}_v$, $\overline{P}_m$, $\overline{F}_T$, and $\overline{M}_{cp}$. Table 3-1 shows the numeric constants used for the evaluation of the sensitivity function. These numbers have been obtained for a Clark Model 1641076 4000 pound cushion tire warehouse lift truck. These numbers are considered "typical" of similarly-designed vehicles.

Parameter	Value/Range	Units	Parameter	Value/Range	Units
X_v	0.3937	Meters	W_{ms}	3300	N
Y_v	-0.7493	Meters			
Z_v	0.6426	Meters	X_D	0.5080	Meters
$\lvert \bar{P}_v \rvert$	1.0988	Meters	$\lvert P_D \rvert$	-0.5080	Meters
W_v	42,000	Newton	X_{R5}	0.3937	Meters
			Y_{R5}	-1.3716	Meters
X_m	0.9552	Meters	Z_{R5}	0.1905	Meters
Y_m	0	Meters			
Z_m	0.4318	Meters	λ_{LRX}	-0.2735	---
			λ_{LRY}	0.9527	---
$\lvert \bar{P}_m \rvert$	1.0574	Meters	λ_{LRZ}	-0.1323	---
X_T	0.9779	Meters	λ_{RRX}	0.2735	---
Y_T	-1.1938	Meters	λ_{RRY}	0.9527	---
Z_T	0.5588	Meters	λ_{RRZ}	-0.1323	---
$\lvert P_T \rvert$	1.6413	Meters			
			$\lvert P_{R5} \rvert$	1.4396	Meters
X_{R2}	0.7874	Meters			
$\lvert P_{R2} \rvert$	0.7874	Meters	$\lvert F_T \rvert$	0 to 114,800	Newtons
			F_{TX}	0	
θ_T	9 to 12.5	Degrees	F_{TY}	0 to 113,000	Newton
			F_{TZ}	0 to 24,800	Newton
θ_m	-10 to +3	Degrees	S_{PLIM}	3150	N-M
θ_x	-30 to +30	Degrees	S_{LRLIM}	715	N-M
θ_y	-30 to +30	Degrees	S_{RRLIM}	715	N-M
			$\lvert \bar{M}_{cp} \rvert$	0 to 14,000	N-M
W_L	0 to 20,000	N	M_{cpx}	0	
			M_{cpy}	0 to 13,800	N-M
W_{mm}	2450	N	M_{cpz}	0 to 2430	N-M

Table 3-1 Numeric Constants Used in the Sensitivity Analysis

The sensitivity analysis for W_V is as follows:

$$S_{W_V}^{Si} = \frac{W_V}{S_i} \overline{\Lambda}^i \cdot \left[\overline{P}_V \times \overline{\lambda}_2 + \delta_{i3} \overline{P}_{R2} \times \overline{\lambda}_g \right] \tag{3-4}$$

$$= \frac{W_V}{S_i} \overline{\Lambda}^i \cdot \left[\left(\overline{P}_V + \delta_{i3} \overline{P}_{R2} \right) \times \overline{\lambda}_g \right] \tag{3-5}$$

$$= \frac{W_V}{S_i} \overline{\Lambda}^i \times \left(\overline{P}_V + \delta_{i3} \overline{P}_{R2} \right) \cdot \overline{\lambda}_g \tag{3-6}$$

$$S_{W_V}^{Si} = \frac{42000}{31,500} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} 0.3937 \\ -0.7493 \\ 0.6426 \end{bmatrix} \cdot \overline{\lambda}_g \tag{3-7}$$

$$S_{W_V}^{Si} = \frac{42,000}{31,500} \begin{bmatrix} 0 \\ -0.6426 \\ -0.7493 \end{bmatrix} \cdot \overline{\lambda}_g \tag{3-8}$$

$$|\overline{\lambda}_g| = 1 \tag{3-9}$$

Let θ_g = the angle formed by the two vectors in the above equation

Then,

$$S_{W_V}^{S_1} = -1.3161 \ \mathrm{Sin}\,\theta_g \tag{3-10}$$

$$\mathrm{Sin}\,\theta_g \leq 1 \tag{3-11}$$

$$S_{W_V}^{S_1} \leq 1.3 \tag{3-12}$$

$$S_{W_V}^{S_2} = \frac{42,000}{7,150} \begin{bmatrix} -0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \times \begin{bmatrix} 0.3937 \\ -0.7493 \\ 0.6426 \end{bmatrix} \cdot \bar{\lambda}_g \tag{3-13}$$

$$S_{W_V}^{S_2} = 5.87 \begin{bmatrix} 0.5131 \\ 0.1237 \\ -0.1701 \end{bmatrix} \cdot \bar{\lambda}_g \tag{3-14}$$

$$S_{W_V}^{S_2} = 3.7 \ \mathrm{Sin}\,\theta_g \tag{3-15}$$

$$\sin\theta_g \leq 1 \tag{3-16}$$

$$S_{W_V}^{S_2} \leq 3.7 \tag{3-17}$$

$$S_{W_V}^{S_3} = \frac{42{,}000}{7{,}150} \begin{bmatrix} 0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \times \begin{bmatrix} 1.1811 \\ -0.7493 \\ 0.6426 \end{bmatrix} \cdot \bar{\lambda}_g \tag{3-18}$$

$$S_{W_V}^{S_3} = \frac{42{,}000}{7{,}150} \begin{bmatrix} 0.5131 \\ -0.3320 \\ -1.3302 \end{bmatrix} \cdot \lambda_g \tag{3-19}$$

$$S_{W_V}^{S_3} = 7.81 \sin\theta_g \tag{3-20}$$

$$\sin\theta_g \leq 1 \tag{3-21}$$

$$S_{W_V}^{S_3} \leq 7.8 \tag{3-22}$$

The sensitivity analysis for W_L is as follows:

$$S_{W_L}^{S_1} = \frac{W_L}{S_1} \overline{\Lambda}^1 \cdot \left[\frac{1}{2}\overline{P}_M \times \overline{\lambda}_g - \delta_{13} \overline{P}_{R2} \times \overline{\lambda}_g\right] \tag{3-23}$$

$$S_{W_L}^{S_1} = \frac{W_L}{S_1} \overline{\Lambda}^1 \times \left(\frac{1}{2}\overline{P}_M - \delta_{13}\overline{P}_{R2}\right) \cdot \overline{\lambda}_g \tag{3-24}$$

$$S_{W_L}^{S_1} = \frac{20{,}000}{31{,}500} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} 0.4826 \\ 0 \\ 0.2159 \end{bmatrix} \cdot \overline{\lambda}_g \tag{3-25}$$

$$S_{W_L}^{S_1} = 0.635 \begin{bmatrix} 0 \\ -0.2159 \\ 0 \end{bmatrix} \cdot \overline{\lambda}_g \tag{3-26}$$

$$S_{W_L}^{S_1} = 0.137 \operatorname{Sin} \theta_g \tag{3-27}$$

$$\operatorname{Sin} \theta_g \leq 1 \tag{3-28}$$

$$S_{W_L}^{S_1} \leq 0.137 \tag{3-29}$$

$$S_{W_L}^{S_2} = \frac{20{,}000}{7{,}150}\begin{bmatrix}-0.2735\\0.9527\\-0.1323\end{bmatrix} \times \begin{bmatrix}0.4826\\0\\0.2159\end{bmatrix} \bullet \bar{\lambda}_g \tag{3-30}$$

$$= 2.797\begin{bmatrix}0.2057\\-0.0048\\-0.4598\end{bmatrix} \bullet \bar{\lambda}_g \tag{3-31}$$

$$= 1.409 \sin \bar{\theta}_g \tag{3-32}$$

$$\sin \theta_g \leq 1 \tag{3-33}$$

$$S_{W_L}^{S_2} \leq 1.4 \tag{3-34}$$

$$S_{W_L}^{S_3} = \frac{20{,}000}{7{,}150}\begin{bmatrix}0.2735\\0.9527\\-0.1323\end{bmatrix} \times \begin{bmatrix}-0.3048\\0\\0.2159\end{bmatrix} \bullet \bar{\lambda}_g \tag{3-35}$$

$$S_{W_L}^{S_3} = 2.797\begin{bmatrix}0.2057\\-0.0187\\0.2904\end{bmatrix} \bullet \bar{\lambda}_g \tag{3-36}$$

$$S_{W_L}^{S_3} = 0.997 \cdot \text{Sin}\,\theta_g \tag{3-37}$$

$$\text{Sin}\,\theta_g \leq 1 \tag{3-38}$$

$$S_{W_L}^{S_3} \leq 1.0 \tag{3-39}$$

The sensitivity analysis for W_{ms} is as follows:

$$S_{W_{MS}}^{S_1} = \frac{W_{MS}}{S_1} \bar{\Lambda}^1 \bullet \left[\frac{1}{2} \bar{P}_M \times \bar{\lambda}_g \right] \tag{3-40}$$

$$S_{W_{MS}}^{S_1} = \frac{W_{MS}}{2S_1} \bar{\Lambda}^1 \times \bar{P}_M \bullet \bar{\lambda}_g \tag{3-41}$$

$$S_{W_{MS}}^{S_1} = \frac{3,300}{2(31,500)} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \times \begin{bmatrix} 0.9652 \\ 0 \\ 0.4318 \end{bmatrix} \bullet \bar{\lambda}_g \tag{3-42}$$

$$S_{W_{MS}}^{S_1} = 0.05238 \begin{bmatrix} 0 \\ -0.4318 \\ 0 \end{bmatrix} \bullet \bar{\lambda}_g \tag{3-43}$$

$$S_{W_{MS}}^{S_1} = -0.02262 \sin\theta_g \tag{3-44}$$

$$\sin \theta_g \leq 1 \tag{3-45}$$

$$S_{W_{MS}}^{S_1} \leq 0.02 \tag{3-46}$$

$$S_{W_{MS}}^{S_2} = \frac{3{,}300}{2(7{,}150)} \begin{bmatrix} -0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \times \begin{bmatrix} 0.9652 \\ 0 \\ 0.4318 \end{bmatrix} \bullet \bar{\lambda}_g \qquad (3\text{-}47)$$

$$S_{W_{MS}}^{S_2} = 0.2308 \begin{bmatrix} 0.4114 \\ -0.0096 \\ -0.9195 \end{bmatrix} \bullet \bar{\lambda}_g \qquad (3\text{-}48)$$

$$S_{W_{MS}}^{S_2} = 0.2325 \operatorname{Sin}\theta_g \qquad (3\text{-}49)$$

$$\operatorname{Sin}\theta_g \leq 1 \qquad (3\text{-}50)$$

$$S_{W_{MS}}^{S_2} = 0.23 \qquad (3\text{-}51)$$

$$S_{W_{MS}}^{S_3} = \frac{3{,}300}{2(7{,}150)} \begin{bmatrix} 0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \times \begin{bmatrix} 0.9652 \\ 0 \\ 0.4318 \end{bmatrix} \bullet \bar{\lambda}_g \qquad (3\text{-}52)$$

$$S_{W_{MS}}^{S_3} = 0.231 \begin{bmatrix} 0.4114 \\ -0.2458 \\ -0.9195 \end{bmatrix} \bullet \bar{\lambda}_g \qquad (3\text{-}53)$$

$$S_{W_{MS}}^{S_3} = 0.24 \operatorname{Sin}\theta_g \tag{3-54}$$

$$\operatorname{Sin}\theta_g \leq 1 \tag{3-55}$$

$$S_{W_{MS}}^{S_3} = 0.24 \tag{3-56}$$

The sensitivity analysis for $\overline{P}_V$ is as follows:

$$S_{P_{Vj}}^{S_i} = \frac{P_{Vj}}{S_i} \overline{\Lambda}^i \bullet \overline{\lambda}_g^j W_V \tag{3-57}$$

where $P_{V1} = X_V$

$P_{V2} = Y_V$

$P_{V3} = Z_V$

$$S_{P_{Vj}}^{S_i} = \frac{P_{Vj} W_V}{S_i} \sin\theta_g \tag{3-58}$$

$$\sin\theta_g \leq 1, \text{ then} \tag{3-59}$$

$$S_{PV_j}^{Si} \leq \frac{P_{Vj} W_V}{Si} \tag{3-60}$$

$$S_{P_{V1}}^{S_1} \leq \frac{(0.3937)(42000)}{31500} = 0.52 \tag{3-61}$$

$$S_{P_{V_1}}^{S_2} \leq \frac{(0.3937)(42000)}{7150} = 2.3 \tag{3-62}$$

$$S_{P_{V_1}}^{S_3} \leq \frac{(0.3937)(42000)}{7150} = 2.3 \tag{3-63}$$

$$S_{P_{V_2}}^{S_1} \leq \frac{(-0.7493)(42000)}{31500} = 1.0 \tag{3-64}$$

$$S_{P_{V_2}}^{S_2} \leq \frac{(-0.7493)(42000)}{7150} = 4.4 \tag{3-65}$$

$$S_{P_{V_2}}^{S_3} \leq \frac{(-0.7493)(42000)}{7150} = 4.4 \tag{3-66}$$

$$S_{P_{V_3}}^{S_1} \leq \frac{(0.6426)\cdot(42000)}{31500} = 0.86 \tag{3-67}$$

$$S_{P_{V_3}}^{S_2} \leq \frac{(0.6426)\cdot(42000)}{7150} = 3.8 \tag{3-68}$$

$$S_{P_{V_3}}^{S_3} \leq \frac{(0.6426)\cdot(42000)}{7150} = 3.8 \tag{3-69}$$

The sensitivity analysis for $\overline{P}_T$ is as follows:

$$S_{P_{T_j}}^{S_i} = \frac{P_{T_j}}{S_i} \overline{\wedge}^{i} \cdot \left[-F_T^{j} \right] \tag{3-70}$$

where $\begin{bmatrix} P_{T1} \\ P_{T2} \\ P_{T3} \end{bmatrix} = \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix}$

maximum $\overline{F}_T$ is $\quad \overline{F}_T = \begin{bmatrix} 0 \\ 113{,}000 \\ 24{,}800 \end{bmatrix}$ (3-71)

$$\overline{F}_T^{1} = \begin{bmatrix} 0 \\ -64{,}400 \\ 95{,}000 \end{bmatrix} \quad \overline{F}_T^{2} = \begin{bmatrix} 64{,}400 \\ 0 \\ 0 \end{bmatrix} \quad \overline{F}_T^{3} = \begin{bmatrix} -95{,}000 \\ 0 \\ 0 \end{bmatrix} \tag{3-72}$$

$$S_{PT_1}^{S_1} = \frac{0.9779}{31{,}500} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ -24{,}800 \\ 113{,}000 \end{bmatrix} = 0 \tag{3-73}$$

$$S_{PT_1}^{S_2} = \frac{0.9779}{7150} \begin{bmatrix} -0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ -24{,}800 \\ 113{,}000 \end{bmatrix} = 5.3 \tag{3-74}$$

$$S^{S_3}_{PT_1} = \frac{0.9779}{7150} \begin{bmatrix} 0.2735 \\ 0.9527 \\ 0.1323 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ -24{,}800 \\ 113{,}000 \end{bmatrix} = 5.3 \tag{3-75}$$

$$S^{S_1}_{PT_2} = \frac{-1.1938}{31{,}500} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \cdot \begin{bmatrix} 24{,}800 \\ 0 \\ 0 \end{bmatrix} = 1.0 \tag{3-76}$$

$$S^{S_2}_{PT_2} = \frac{-1.1938}{7150} \begin{bmatrix} -0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} 24{,}800 \\ 0 \\ 0 \end{bmatrix} = 1.1 \tag{3-77}$$

$$S^{S_3}_{PT_2} = \frac{-1.1938}{7150} \begin{bmatrix} 0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} 24{,}800 \\ 0 \\ 0 \end{bmatrix} = 1.1 \tag{3-78}$$

$$S^{S_1}_{PT_3} = \frac{0.5588}{31{,}500} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \cdot \begin{bmatrix} -113{,}000 \\ 0 \\ 0 \end{bmatrix} = 2.0 \tag{3-79}$$

$$S^{S_2}_{PT_3} = \frac{0.5588}{7150} \begin{bmatrix} -0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} -113{,}000 \\ 0 \\ 0 \end{bmatrix} = 2.4 \tag{3-80}$$

$$S^{S_3}_{PT_3} = \frac{0.5588}{7150} \begin{bmatrix} 0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} -113{,}000 \\ 0 \\ 0 \end{bmatrix} = 2.4 \tag{3-81}$$

The sensitivity analysis for $\overline{P}_m$ is as follows:

$$S_{P_{mj}}^{S_i} = \frac{P_{mj}}{S_i} \quad \overline{\Lambda}^i \cdot \left[\overline{F}_T^j + \frac{1}{2} \overline{\lambda}_g^j \ (W_L + W_{ms}) \right] \tag{3-82}$$

where $\begin{bmatrix} P_{m_1} \\ P_{m_2} \\ P_{m_3} \end{bmatrix} = \begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix}$

$$\overline{F} = \begin{bmatrix} 0 \\ 113,000 \\ 24,800 \end{bmatrix} \qquad \begin{matrix} W_L = 20,000 \\ W_{ms} = 3,300 \end{matrix} \tag{3-83}$$

$$S_{P_{m_1}}^{S_1} = \frac{0.9652}{31,500} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \left(\begin{bmatrix} 0 \\ -24,800 \\ 113,000 \end{bmatrix} + \frac{23300}{2} \begin{bmatrix} 0 \\ -\cos\theta_z \\ \cos\theta_x \end{bmatrix} \right) = 0 \tag{3-84}$$

$$S_{P_{m_1}}^{S_2} = \frac{0.9652}{7150} \begin{bmatrix} -0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \left(\begin{bmatrix} 0 \\ -24,800 \\ 113,000 \end{bmatrix} + \frac{23,300}{2} \begin{bmatrix} 0 \\ -\cos\theta_z \\ \cos\theta_x \end{bmatrix} \right) \tag{3-85}$$

$$\text{Let} \quad \cos\theta_z = 1, \quad \cos\theta_x = -1 \tag{3-86}$$

$$S_{P_{m_1}}^{S_2} \leq 4.3 \tag{3-87}$$

$$S^{S_3}_{Pm_1} = \frac{0.9652}{7150}\begin{bmatrix}0.2735\\0.9527\\-0.1323\end{bmatrix}\left(\begin{bmatrix}0\\-24,800\\113,000\end{bmatrix} + \frac{23,300}{2}\begin{bmatrix}0\\-\cos\theta_Z\\\cos\theta_X\end{bmatrix}\right) \quad (3\text{-}88)$$

Let $\cos\theta_Z = 1, \qquad \cos\theta_X = -1$ (3-89)

$$S^{S_3}_{Pm_1} \leq 4.3 \quad (3\text{-}90)$$

$$S^{S_1}_{Pm_2} = 0 \quad (3\text{-}91)$$

$$S^{S_2}_{Pm_2} = 0 \quad (3\text{-}92)$$

$$S^{S_3}_{Pm_3} = 0 \quad (3\text{-}93)$$

$$S^{S_1}_{Pm_3} = \frac{0.4318}{31,500}\begin{bmatrix}1\\0\\0\end{bmatrix}\left(\begin{bmatrix}-113,000\\0\\0\end{bmatrix} + \frac{23,300}{2}\begin{bmatrix}-\cos\theta_y\\\cos\theta_X\\0\end{bmatrix}\right) \quad (3\text{-}94)$$

Let $\cos\theta_y = 1$ (3-95)

$$S^{S_1}_{Pm_3} \leq 1.9 \quad (3\text{-}96)$$

$$S^{S_2}_{P_{m_3}} = \frac{0.4318}{7150} \begin{bmatrix} -0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \left(\begin{bmatrix} -113,000 \\ 0 \\ 0 \end{bmatrix} + \frac{23,300}{2} \begin{bmatrix} -\text{Cos } \theta y \\ \text{Cos } \theta x \\ 0 \end{bmatrix} \right) \tag{3-97}$$

Let $\text{Cos } \theta x = 1, \quad \text{Cos } \theta y = 1$ (3-98)

$$S^{S_2}_{P_{m_3}} \leq 2.7 \tag{3-99}$$

$$S^{S_3}_{P_{m_3}} = \frac{0.4318}{7150} \begin{bmatrix} 0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \left(\begin{bmatrix} -113,000 \\ 0 \\ 0 \end{bmatrix} + \frac{23,300}{2} \begin{bmatrix} -\text{Cos } \theta y \\ \text{Cos } \theta x \\ 0 \end{bmatrix} \right) \tag{3-100}$$

Let $\text{Cos } \theta x = -1, \quad \text{Cos } \theta y = 1$ (3-101)

$$S^{S_3}_{P_{m_3}} \leq 2.7 \tag{3-102}$$

The sensitivity analysis for $\overline{F}_T$ is as follows:

$$S^{S_i}_{F_{Tj}} = \frac{F_{Tj}}{S_i} \overline{\Lambda}^i \cdot \left[-(P^j_m - P^j_T) \right] \tag{3-103}$$

$$S^{S_1}_{FT_1} = 0 \tag{3-104}$$

$$S^{S_2}_{FT_1} = 0 \tag{3-105}$$

$$S^{S_3}_{FT_1} = 0 \tag{3-106}$$

$$S^{S_1}_{FT_2} = \frac{113{,}000}{31{,}500} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \cdot \begin{bmatrix} -0.1270 \\ 0 \\ 0 \end{bmatrix} = 0.5 \tag{3-107}$$

$$S^{S_2}_{FT_2} = \frac{113{,}000}{7150} \begin{bmatrix} -0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} -0.1270 \\ 0 \\ 0 \end{bmatrix} = 2.0 \tag{3-108}$$

$$S^{S_3}_{FT_2} = \frac{113{,}000}{7150} \begin{bmatrix} 0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} -0.1270 \\ 0 \\ 0 \end{bmatrix} = 2.0 \tag{3-109}$$

$$S^{S_1}_{FT_3} = \frac{23{,}300}{31{,}500} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \cdot \begin{bmatrix} -1.1938 \\ 0 \\ 0 \end{bmatrix} = 0.9 \tag{3-110}$$

$$S^{S_2}_{FT_3} = \frac{23{,}300}{7150} \begin{bmatrix} -0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} -1.1938 \\ 0 \\ 0 \end{bmatrix} = 1.1 \tag{3-111}$$

$$S^{S_3}_{FT_3} = \frac{23{,}300}{7150} \begin{bmatrix} 0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} -1.1938 \\ 0 \\ 0 \end{bmatrix} = 1.1 \qquad (3\text{-}112)$$

The sensitivity analysis for $\overline{M}_{cp}$ is as follows:

$$S^{S_i}_{M_{cpj}} = \frac{M_{cpj}}{S_i} \overline{\Lambda}^i \cdot \begin{bmatrix} -e_j \end{bmatrix} \qquad (3\text{-}113)$$

$$\text{where} \quad e_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad e_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \quad e_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$S^{S_1}_{M_{cp1}} = 0 \qquad (3\text{-}114)$$

$$S^{S_2}_{M_{cp1}} = 0 \qquad (3\text{-}115)$$

$$S^{S_3}_{M_{cp1}} = 0 \qquad (3\text{-}116)$$

$$S^{S_1}_{M_{cp2}} = \frac{13{,}800}{31{,}500} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix} = 0 \qquad (3\text{-}117)$$

$$S^{S2}_{Mep2} = \frac{13,800}{7150} \begin{bmatrix} -0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix} = 1.8 \tag{3-118}$$

$$S^{S3}_{Mep2} = \frac{13,800}{7150} \begin{bmatrix} 0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix} = 1.8 \tag{3-119}$$

$$S^{S1}_{Mep3} = \frac{2430}{31,500} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} = 0 \tag{3-120}$$

$$S^{S2}_{Mep3} = \frac{2430}{7150} \begin{bmatrix} -0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} = 0.045 \tag{3-121}$$

$$S^{S3}_{Mep3} = \frac{2430}{7150} \begin{bmatrix} 0.2735 \\ 0.9527 \\ -0.1323 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} = 0.045 \tag{3-122}$$

RESULTS

The results of the sensitivity analysis are summarized in Table 3-2. Parameters which are determined as a result of a measurement via a transducer--notably W_L, $\overline{F}_T$, and $\overline{M}_{cp}$,--were all found to be significant. In addition specified constants W_v, $\overline{P}_v$, $\overline{P}_T$, and $\overline{P}_m$, were found to be significant. Only the weight of the stationary portion of the mast (W_{ms}) was found to be noncritical.

The following conclusions may be drawn from the analysis:

1. All measured parameters <u>are</u> required. Thus, no transducers may be eliminated.

2. All constants which specify vehicle geometry and etc., except one are critical. Therefore, it will be necessary to specify these for the particular vehicle model.

Answering the originally posed questions, none of the terms can be ignored and all have a significant effect on the overall determination of stability.

Term	S_1	S_2	S_3
W_V	1.3	3.7	7.8
W_L	0.14	1.4	1.0
W_{MS}	0.02	0.23	0.24
X_V	0.5	2.3	2.3
Y_V	1.0	4.4	4.4
Z_V	0.86	3.8	3.8
X_T	0	5.3	5.3
Y_T	1.0	1.1	1.1
Z_T	2.0	2.4	2.4
X_M	0	4.3	4.3
Y_M	0	0	0
Z_M	1.9	2.7	2.7
F_{TX}	0	0	0
F_{TY}	0.5	2.0	2.0
F_{TZ}	0.9	1.1	1.1
M_{CPX}	0	0	0
M_{CPY}	0	1.8	1.8
M_{CPZ}	0	0.05	0.05

Table 3-2 Results of Sensitivity Analysis

CHAPTER IV

IMPLEMENTATION OF THEORY

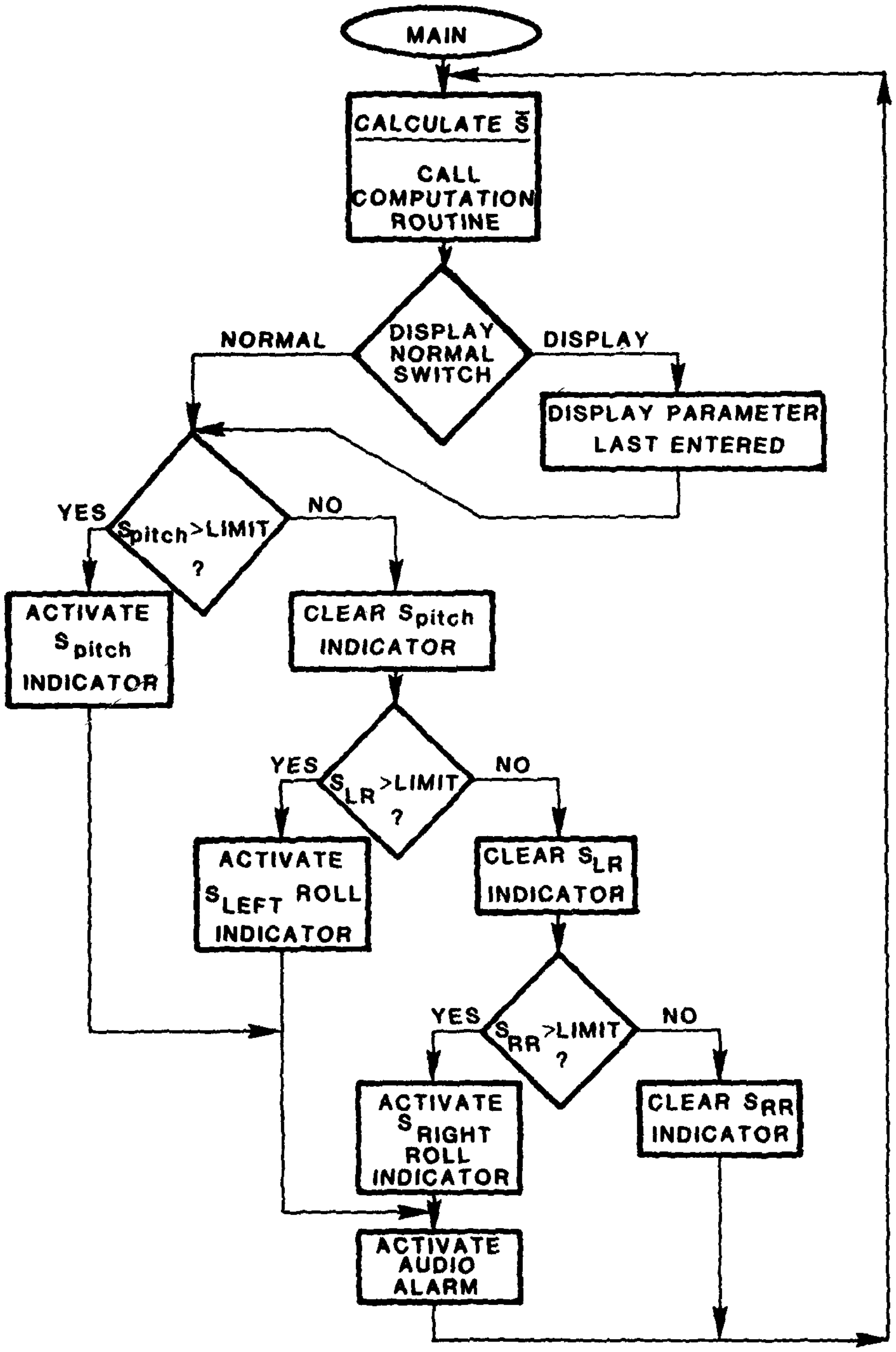
This section will detail the method utilized to implement the Stability Monitor Theory. Since the Monitor is based on a microcomputer, implementation of the Monitor logic is performed by "Software" as opposed to "hardware". The sequential logic operations are coded so the microcomputer can execute these operations repetitively. The coding is done in a high-level language designed for microcomputer program development with specific commands written for this application.

LOGIC FLOW

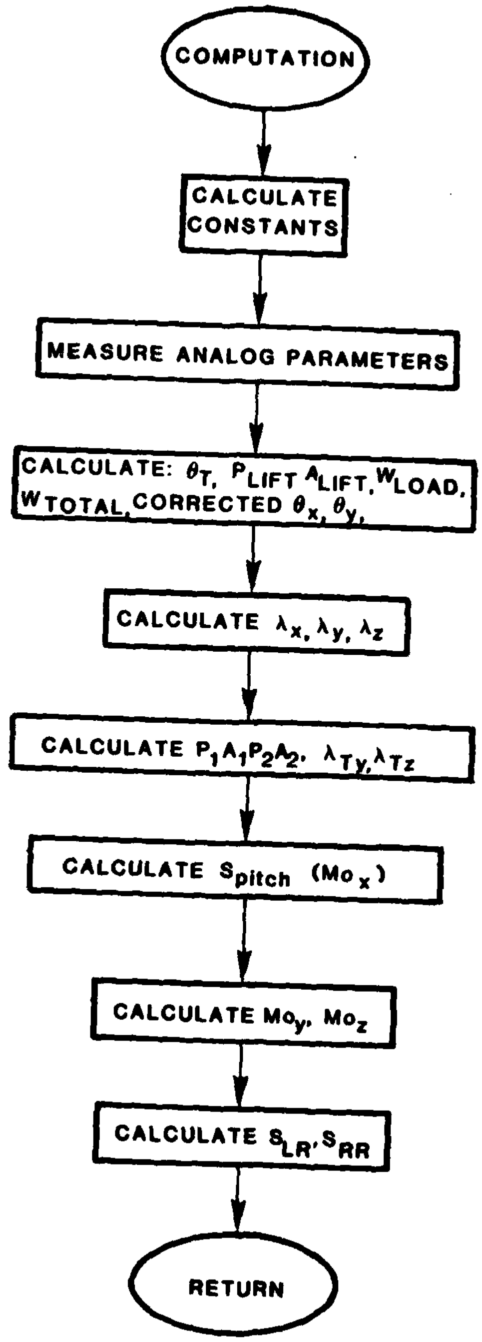
The Stability Monitor logic is performed in two distinct blocks- the Main Program and Computation Routine. The Main Program is entered when the "RUN" switch is activiated, immediately transferring to the Computation Algorithm, which is a sub-program. On return from the subroutine, Main makes some basic decisions regarding stability. The proper action is taken to process indicators/alarms and the entire process is then repeated. Figures 4-1 and 4-2 are flow charts of the program logic.

FP/1 IMPLEMENTATION

The Stability Monitor program logic was coded in a microcomputer language (dubbed FP/1) developed by the FPRC - O.S.U. for Hydraulic applications. The specifics of FP/1 are discussed in Appendix A.



Main Program Flowchart
Fig. 4-1



Computation Algorithm
Fig. 4-2

This version of FP/1 was tailored to the Stability Monitor requirements.

High Level Microcomputer Languages

The computer language used here is a High Level Language (HLL), instead of Assembly language. This is in opposition to the traditional approach to microprocessor software design, where all logic is written in assembler code and committed to PROM for automatic controller operation on power-up.

Some advantages of the HLL approach are ease of programming due to fewer lines of code required and English-like instructions; drastically reduced firmware development time; reduced need for comments and detailed flow charting which reduces documentation time and bulk; encouragement of Structured Programming practices and program portability.

The HLL used in the Stability Monitor (FP/1) is a BASIC-like interpreter written specifically for the Intel 8085 μC and scaled to fit in 6 k bytes of memory. Thus, execution time is relatively slow compared with assembly code, but a large amount of memory is not required to store this HLL, as it would be for a compiler or enhanced interpreter. This slower execution speed is still adequate for use in this application.

The following paragraphs discuss the specific items involved with Stability Monitor implementation.

Stability Monitor Equations

The goal of the Monitor is to determine when and if an unstable

WFT configuration occurs and to activate the appropriate alarms. To this end, three scalar equations (vector components) are performed in the Computational Algorithm to determine S_{pitch}, $S_{left\ roll}$, and $S_{right\ roll}$ (the Stability Indexes). These equations are shown below.

1) $S_{pitch} = M_{ox}$

$$= Y_v W_v \lambda_z - Z_v W_v \lambda_y + [(P_1 A_1 - P_2 A_2) \mathrm{Sin}\theta_T]\ (Y_T)$$
$$- [(P_1 A_1 - P_2 A_2) \mathrm{Cos}\theta_T]\ (Z_T - Z_M) + \tfrac{1}{2}(-Z_m W_L \lambda_y)$$

2) $S_{LR} = \bar{\lambda}_{LR} \cdot \bar{M}_o = \lambda_{LRX}(M_{ox}) + \lambda_{LRY}(M_{oy}) + \lambda_{LRZ}(M_{OZ})$

$$= \lambda_{LRX}(S_{pitch}) + \lambda_{LRY}[Z_v W_v \lambda_x - X_v W_v \lambda_x + \tfrac{1}{2}(Z_m W_L \lambda_x - X_m W_L \lambda_z)$$
$$+ X_D \Delta F_{mz} \lambda_{mz}] + \lambda_{LRZ}[X_v W_v \lambda_y - y_v W_v \lambda_x + \tfrac{1}{2}(X_m W_L \lambda_y)$$
$$- (X_D \Delta F_{my} \lambda_{my})]$$

3) $S_{RR} = \bar{\lambda}_{RR} \cdot \bar{M}_{R2} = \lambda_{RRX}(M_{R2X}) + \lambda_{RRY}\ (M_{R2Y}) + \lambda_{RRZ}(M_{R2Z})$

$$= \lambda_{RRX}[M_{ox} + P_{R2Y} W \lambda_z - P_{R2Z} W \lambda_y] + \lambda_{RRY}[M_{oy} + P_{R2Z} W \lambda_x$$
$$- P_{R2X} W \lambda_Z] + \lambda_{RRZ}[M_{oz} + P_{R2X} W \lambda_y - P_{R2y} W \lambda_x]$$

But: $P_{R2Y} = P_{R2Z} = 0$

Therefore: equation 3 becomes equation 4:

4) $S_{RR} = \lambda_{RRX}[M_{ox}] + \lambda_{RRY}[M_{oy} + P_{R2X} W \lambda_z] + \lambda_{RRZ}[M_{oz} - P_{R2X} W \lambda_y]$

To reduce equations (1,2,4) to a form easily implemented with the programming language (FP/1), make the following parameter assignments.

Let:

$A = Y_v W_v$ $\qquad E = X_v W_v$ $\qquad Z = Z_T - Z_M$

$B = Z_v W_v$ $\qquad F = X_m W_L$ $\qquad K\delta = X_D \Delta F_M$

$C = Z_m W_L$ $\qquad W = W_v + W_L$

Now the equations for implementation appear in this form:

$$5)\quad S_{pitch} = A^*\lambda_z - B^*\lambda_y + [(P_1A_1 - P_2A_2)\ (\sin \theta_T)(Y_T)]$$

$$- [(P_1A_1 - P_2A_2)\ (\cos \theta_T)^*Z] - (C/2\ ^*\lambda_y)$$

$$6)\quad S_{LR} = \lambda_{LRX}(S_{pitch}) + \lambda_{LRY}(M_{oy}) + \lambda_{LRZ}(M_{oz})$$

$$7)\quad S_{RR} = \lambda_{RXX}(S_{pitch}) + \lambda_{RRY}(M_{oy} + I\lambda_z) + \lambda_{RRZ}\ (M_{oz} - I\lambda_y)$$

where: $M_{oy} = [(B^*\lambda_x - E^*\lambda_z) + \frac{1}{2}\ (C^*\lambda_x - F^*\lambda_z) + (K\delta^*\ \lambda m_z)]$

$$M_{oz} = [(E^*\lambda_y - A^*\lambda_x) + \tfrac{1}{2}\ (F^*\lambda_y) - K\delta^*\ \lambda_{my})]$$

A*, B*, C*, D*, E*, F* are constants

Tilt Cylinder Angle Derivation

One parameter (θ_T) cannot be directly measured. An indirect method was devised where the relationship between a known parameter and the

desired one allows calculation of it. Thus θ_T is derived from θ_m using a linear model and the Least Squares Curve Fit technique. The four data points below were measured and used to fit the straight line function.

i	$X=\theta_m$	$Y=\theta_T$
1	2.3^o	9.0
2	0.0	10.0
3	-5.0	11.3
4	-11.8	12.5

The relationship between θ_m and θ_T is a straight line represented by the equation: $\theta_T = 9.81 - .242\theta_m$.

<u>Angle Corrections</u>

The angle measurements for both vehicle orientation and mast angle are made using the Humphrey pendulum-type transducer. Therefore the output is erroneous when it makes an angle with more than one plane. The angle transducer outputs must be corrected by a factor of the co sine of the "insensitive" angle, i.e., if θ_y is 10^o and θ_x is 10^o, the transducer output of θ_y must be corrected by $\cos\theta_x$. These correction terms are included in FP/1 statements, noted in the narrative. Also, the measured mast angle must be corrected for both $\theta_x \neq 0$(via $\cos\theta_x$), and for actual vehicle angles along the Y axis ($\theta_y \neq 0$).

Tilt Cylinder Corrections

The problem of reduced pressure in the tilt cylinder when extended to the mechanical mast stops is solved here by sensing the (max. and min.) mast positions with mechanical limit switches. When either a forward or backward stop is reached, P8 or P9 have a value of +5 volts and the Monitor will use the last tilt cylinder pressures to determine the force F_T, preventing an erroneously small force calculation when in this configuration. Otherwise, when the mast is not resting on a stop, the values of P8 and P9 are zero volts. This correction is performed in FP/1 interpreter statements, and therefore the slower execution speed combined with the polling technique create a small probability that an occasional Limit condition may pass unnoticed.

Calculation of λ_z

The direction cosine for the Z axis (λ_z) cannot be feasibly measured in a direct fashion. However, it can be computed from the definition of the direction cosine. The magnitude of the vector $\overline{\lambda_v}$ must always be one. Therefore, measuring θ_x and θ_y permits λ_z to be derived from this relationship:

$$\lambda_z = \text{Cos } \theta_z = - \left[1 - \text{Cos}^2\theta_x - \text{Cos}^2\theta_y \right]^{\frac{1}{2}}$$

The minus sign is included because (λ_z) will always be negative unless the vehicle is overturned.

Stability Limits

The parameters P44, P45, and P46 are the limits for vehicle sta-

Parameter	Equation Variable	Representation	Metric Value	Units
P1	P_1	Tilt Cylinder Pressure (rod side)	-----	Newtons-Meter^2
P2	P_2	Tilt Cylinder Pressure (head side)	-----	Newtons-Meter^2
P3	P_{Lift}	Lift Cylinder Pressure	-----	Newtons-Meter^2
P4	θ_x	Angle 1 - X axis with Horz.	-----	Degrees
P5	θ_y	Angle 2 - Y axis with Horz.	-----	Degrees
P6	θ_m	Angle 3 - Mast angle W/Vert.	-----	Degrees
P7	$X_D X \Delta F_m$	(σ) Side Strain on Mast	-----	Microstrain
P8	Limit	Limit switches for P1, P2 (tilt cylinder)	-----	-----
P9	Limit		-----	-----
P10	Y_v	Y component; c.g. vector	-0.7493	Meters
P11	Z_v	Z component; c.g. vector	0.6426	Meters
P12	$X_v W_v$	Product of vehicle weight and position vector for c.g. of vehicle	-----	Newton-Meter
P13	$Y_v W_v$		-----	Newton-Meters
P14	$Z_v W_v$		-----	Newton-Meters
P15	$Z_T - Z_m$	-----	-----	Meters
P16	Z_m	Z component, Mast vector	0.4318	Meters
P17	Z_T	Z component, Tilt cylinder vector	0.5588	Meters
P18	θ_T	Tilt cylinder angle W/Horz.	-----	Degrees
P19	X_m	X component, Mast vector	0.9493	Meters
P20	λ_{LRX}	Direction cosines for Left roll axis	-0.2735	-----
P21	λ_{LRY}		0.9527	-----
P22	λ_{LRZ}		-0.1323	-----
P23	A_2	Tilt cylinder piston area (head side)	.0235	Meters^2
P24	A_1	Tilt cylinder piston area (rod side)	.01707	Meters^2
P25	A Lift	Lift cylinder piston area	.0025	Meters^2

Table 4-1

Geometric Parameter Values and Program Variable Descriptions

Parameter	Equation Variable	Representation	Metric Value	Units
P26	Y_T	Y component of Tilt cylinder position	-0.5969	Meters
P27	K	Scaling factor for σ	1.371703×10^8	N-m/$\mu\sigma$
P28	W_m	Mast weight (stationary)	3620.0	Newtons
P29	P_{R2X}	Position (x component) to Reaction Force	0.8000	Meters
P30	X_v	X component, c.g. Pos. Vector	0.4000	Meters
P31	W_v	Weight of vehicle (Less Mast)	24715.3	Newtons
P32	S_{pitch}	Stability index for Pitch Axis	-----	Newton-Meter
P33	S_{LR}	Stability index for Left Roll Axis	-----	Newton-Meter
P34	S_{RR}	Stability index for Right Roll Axis	-----	Newton-Meter
P35	W_L	Weight of Load	-----	Newtons
P36	λ_x		-----	-----
P37	λ_y	Vehicle direction cosines	-----	-----
P38	λ_z		-----	-----
P39	Cos θ_T	Cosine of tilt cylinder Angle	-----	-----
P40	Sin θ_T	Sine of tilt cylinder Angle	-----	-----
P41	λ_{RRX}		0.2735	-----
P42	λ_{RRY}	Direction cosines for Left Roll Axis	0.9527	-----
P43	λ_{RRZ}		-0.1323	-----
P44	-----	A_{Pitch} Limit	1000.0	Newton-Meter
P45	-----	S_{LR} Limit	800.0	Newton-Meters
P46	-----	S_{RR} Limit	800.0	Newton-Meter
W	$W_v + W_L$	Total (Vehicle + Load) Weight	-----	Newtons
F	$X_m W_L$		-----	Newton-Meters
I	$P_{RZX} W$	Program Variables	-----	Newton-Meters
M2	M_{oy}		-----	Newton-Meters
M3	M_{oz}		-----	Newton-Meters

Table 4-1 (Continued)

bility. These were determined empirically, to provide a conservative value for comparison with the calculated stability index of the Monitor. These values will of course be different for each vehicle model. Therefore, they were included in the user input parameter section and are listed in Table 4-1.

Parameter Assignments

Table 4-1 contains all the geometric parameters and program variables with short descriptions and actual values used (CLARK WFT) by FPRC-OSU for testing purposes. These values are entered on the Monitor front panel keypad and stored in CMOS RAM. The parameters without values are program variables and are not user entered; however, they can be examined from the front-panel display for analysis.

Stability Monitor Program

The actual Monitor software is listed here in its entirety. Comments are provided for documentation.

Line No.	MAIN PROGRAM Statement		COMMENTS (Preceded by semi-colon)
5	MEAS P8, P9	;	Input Limit Switches
6	If P8>2048 then 9	;	On FWD. stop?
7	If P9>2048 then 9	;	On REAR stop?
8	MEAS P1, P2	;	NO, measure tilt pressures
9	MEAS P3, P4, P5, P6, P7	;	Measure analog parameters
10	Go Sub 90	;	Stability calculation routine

15	Displ	; Display parameter keyed last
20	If P32>P44 then 60	; $S_P > S_P Lim$?
25	Reset SV2	; Clear Indicator
30	If P33>P45 then 62	; $S_{LR} > S_{LR}$ Lim?
35	Reset SV1	; Clear
40	If P34>P46 then 64	; $S_{RR} > S_{RR} Lim$?
45	Reset SV3	; Clear
50	Go to 5	; Begin again
60	SET SV2	; Set S_P alarm
61	Go to 30	
62	Set SV1	; Set S_{LR} alarm
63	Go to 40	
64	SET SV3	; Set S_{RR} alarm
70	Go to 5	

<u>COMPUTATION ALGORITHM</u>

90	LET	P12 = P30 * P31	; $X_v W_v$
100	LET	P13 = P10 * P31	; $Y_v W_v$
102	LET	P14 = P11 * P31	; $Z_v W_v$
104	LET	P15 = P17 - P16	; $Z_T - Z_M$
106	LET	P6 = P6 * COS P4	; Correct θ_m
108	LET	J = P4 * COS P5	; θ_x Corrected
110	LET	P5 = P5 * COS P4	; θ_y Corrected
112	LET	P4 = J	
115	LET	P6 = P6 - P5	; Adjust θ_m for $\theta_y \neq 0$

120	LET	P18 = 0.242 * P6	; Calc. θ_T
122	LET	P18 = 9.81 - P18	
124	LET	P35 = P3 * P25	; $P_{Lift}A_{Lift}$
126	LET	P35 = P35/Cos P6	
128	LET	P35 = P35/Cos P4	
130	LET	P35 = P35 + P28	; $W_{Load} = \frac{P_L A_L}{COS\ \theta_m\ COS\ \theta_x} + W_{ms}$
132	LET	F = P19 + P35	; $X_m W_L = F$
134	LET	W = P35 + P31	; $W_v + W_L = W$
140	IF	P4<0 Then 400	; Adjust for neg. angles
142	LET	P36 = -SIN P4	; $\lambda_x = -SIN\ \theta_x$
144	IF	P5<0 Then 405	
146	LET	P37 = SIN P5	; $\lambda_y = SIN\ \theta_y$
148	LET	J=COS P4 * COS P4	; $COS^2\theta_x$
150	LET	K = 1-J	; $1-COS^2\theta_x$
152	LET	J=COS P5 * COS P5	; $COS^2\theta_y$
154	LET	K = K - J	
156	LET	K = -K	; GET Pos. value
158	LET	P38 = -SQRT K	; $\lambda_z = 1-COS^2\theta_x - COS^2\lambda_y$
200	LET	C = P16 * P35	; $Z_m W_L$
206	LET	I = P29 * W	; $PR2_x * W$
208	LET	J = P1 * P24	; P_1A_1
210	LET	K = P2 * P23	; P_2A_2
212	LET	U = J - K	; $(P_1A_1 - P_2A_2)$

214 LET P39 = COS P18 ; SIN θ_T (λ_{TZ})

216 LET P40 = SIN P18 ; COS θ_T (λ_{TY})

CALC. $S_{pitch} \rightarrow (M_{ox})$

230 LET J = P13 * P38 ; $Y_v W_v \lambda_z$

232 LET K = P14 * P37 ; $Z_v W_v \lambda_y$

234 LET V = J-K ; $A\lambda_z - B\lambda_y$

236 LET J = U * P40

238 LET J = P26 * J ; $(Y_T)(P_1A_1 - P_2A_2)\text{SIN } \theta_T = F_{Tz}$

240 LET U = U * P39

242 LET K = U * P15 ; $(Z_T - Z_M)(P_1A_1 - P_2A_2)\text{COS}\theta_T = F_{Ty}$

244 LET U = C/2

246 LET U = U * P37 ; $C/2 * \lambda_y$

248 LET J = J + V

250 LET K = K - U

252 LET P32 = J - K ; S_{pitch}

CALC. $M_{oy} \rightarrow (M2)$

260 LET J = P14 * P36 ; $Z_v W_v \lambda_x$

262 LET K = P12 * P38 ; $X_v W_v \lambda_z$

264 LET U = J - K ; $U = B * \lambda_x) - E * \lambda_z$

266 LET J = C * P36 ; $Z_m W_L \lambda_x$

268 LET K = F * P38 ; $X_m W_L \lambda_z$

270 LET K = J - K

```
272   LET   K    = K/2          ;  ½(  * λ_x - F * λ_z)
274   LET   J    = P27 * P7     ;  (X_D * ΔF_m)K
276   LET   J    = J * COS P6   ;  X_D * ΔF_m * λ_mz
278   LET   K    = U+K
280   LET   M2   = J+K          ;  M_oy→(M2)
```

CALC, M_{oz} (M3)

```
290   LET   J    = P12 * P37
300   LET   K    = P13 * P36
310   LET   U    = J-K          ;  E * λ_y - A * λ_x
315   LET   J    = F * P37
320   LET   K    = J/2          ;  ½(F * λ_y)
325   LET   J    = P27 * P7     ;  Kλ =  X_D * ΔF_m
330   IF    J<0 Then 410        ;  correct if neg. for sine
335   LET   J    = J * SIN P6   ;  X_D * ΔF_m * λ_my
340   LET   K    = U+K
345   LET   M_3  = K-J          ;  M_oz→(M3)
```

CALC. $S_{LR} = \overline{\lambda_{LR}} \cdot \overline{M_o}$

```
350   LET   J    = P20 * P32    ;  λ_LRX (M_ox)
355   LET   K    = P21 * M2     ;  λ_LRY (M_oy)
360   LET   U    = P22 * M3     ;  λ_LRZ (M_oz)
365   LET   P33  = J+K
370   LET   P33  = P33+U        ;  SLR
```

CALC. $S_{RR} = \overline{\lambda_{RR}} \cdot \overline{MR_2}$

375	LET J = I * P38	; $PR_2W * \lambda_z$
380	LET J = M_2+J	
383	LET J = J * P42	; $\lambda_{RRY}[M_{oy}+I\lambda_y]$
385	LET K = I * P37	
388	LET K = M3-K	
390	LET K = K * P43	; $\lambda_{RRZ}[M_{oz}-I\lambda_y]$
393	LET J = J+K	
395	LET K = P32 * P41	
397	LET P34 = J+K	; $-S_{RR}$
398	LET P34 = -P34	
399	RETURN	; End of computation subroutine

Corrections for Negative Angles

400	LET P36 = SIN P4	; correct for λ_x
402	GO TO 144	
405	LET P37 = -SIN P5	; correct for λ_y
408	GO TO 148	
410	LET J = -SIN P6 * J	; correct M_{oz}
415	GO TO 340	
420	END	

Geometric Parameters

The derivation of certain geometric parameters is not obvious, and these are shown below:

a) $\bar{P}_T = \begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} \triangleq \bar{P}_{T_1} + \bar{P}_{T_2}$

This is the sum of the two tilt cylinder position vectors.

b) $\bar{P}_M = \begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix} \triangleq \bar{P}_{m_1} + \bar{P}_{m_2} = \begin{bmatrix} X_{m1x} \\ o \\ o \end{bmatrix} + \begin{bmatrix} X_{m2x} \\ o \\ o \end{bmatrix} = \begin{bmatrix} .15558 + .63183 \\ o \\ o \end{bmatrix}$

This is the sum of the mast support position vectors.

c) $\bar{P}_D = \begin{bmatrix} X_D \\ Y_D \\ Z_D \end{bmatrix} \triangleq \bar{P}_{m_1} - \bar{P}_{m_2} = \begin{bmatrix} X_{m1x} \\ o \\ o \end{bmatrix} - \begin{bmatrix} X_{m2x} \\ o \\ o \end{bmatrix}$

This is the difference of the two mast support position vectors. Also: $Y_D = Z_D = 0$ due to vehicle geometry.

Therefore: $P_D = \begin{bmatrix} X_D \\ o \\ o \end{bmatrix}$; but $X_D * F_m$ is directly measured via the strain Line as implemented here.

d) $P_V = \begin{bmatrix} X_v \\ Y_v \\ Z_v \end{bmatrix} \triangleq$ the position vector to the WFT vehicle center of gravity. This is defined by the manufacturer.

All these measurements are taken with respect to the vehicle coordinate system, described in the theory section. The areas (A_1, A_2, A_3) were obtained by calculation from a known load and cylinder pressure, measured via the system pressure transducers.

CHAPTER V

WFT STABILITY MONITOR HARDWARE DESCRIPTION

This section describes the function of the various hardware modules comprising the WFT STABILITY MONITOR. Basic overall system operation is explained, and figure 5-1 is a block diagram of the overall system. The circuit schematics and specifications are detailed in the appendix.

MICROCOMPUTER CONFIGURATION

The heart of the Stability Monitor is the M-85 microcomputer (μC) developed by the Fluid Power Research Center, Oklahoma State University. The Intel 8085 microprocessor forms the nucleus for the μC. This is an 8-bit μP with an average operating speed of 1.2 micro-second per instruction. There is one thousand (1K) bytes of CMOS read/write memory available for system parameter storage and PP/1 scratchpad memory. The interpreter itself resides in six thousand (6K) bytes of Erasable Programmable Read Only Memory (EPROM). This memory is non-volatile; thus, the interpreter is permanently stored in the system.

The microcomputer controls monitor operation via the I/O system, which consists of two Input/Output cards, a Keyboard/Display card, and front panel switches/indicators. A 12-bit Analog-to-Digital (A/D) Converter card and 8 channel signal conditioning card provide transducer input for the necessary analog parameters. The microcomputer has the capability to

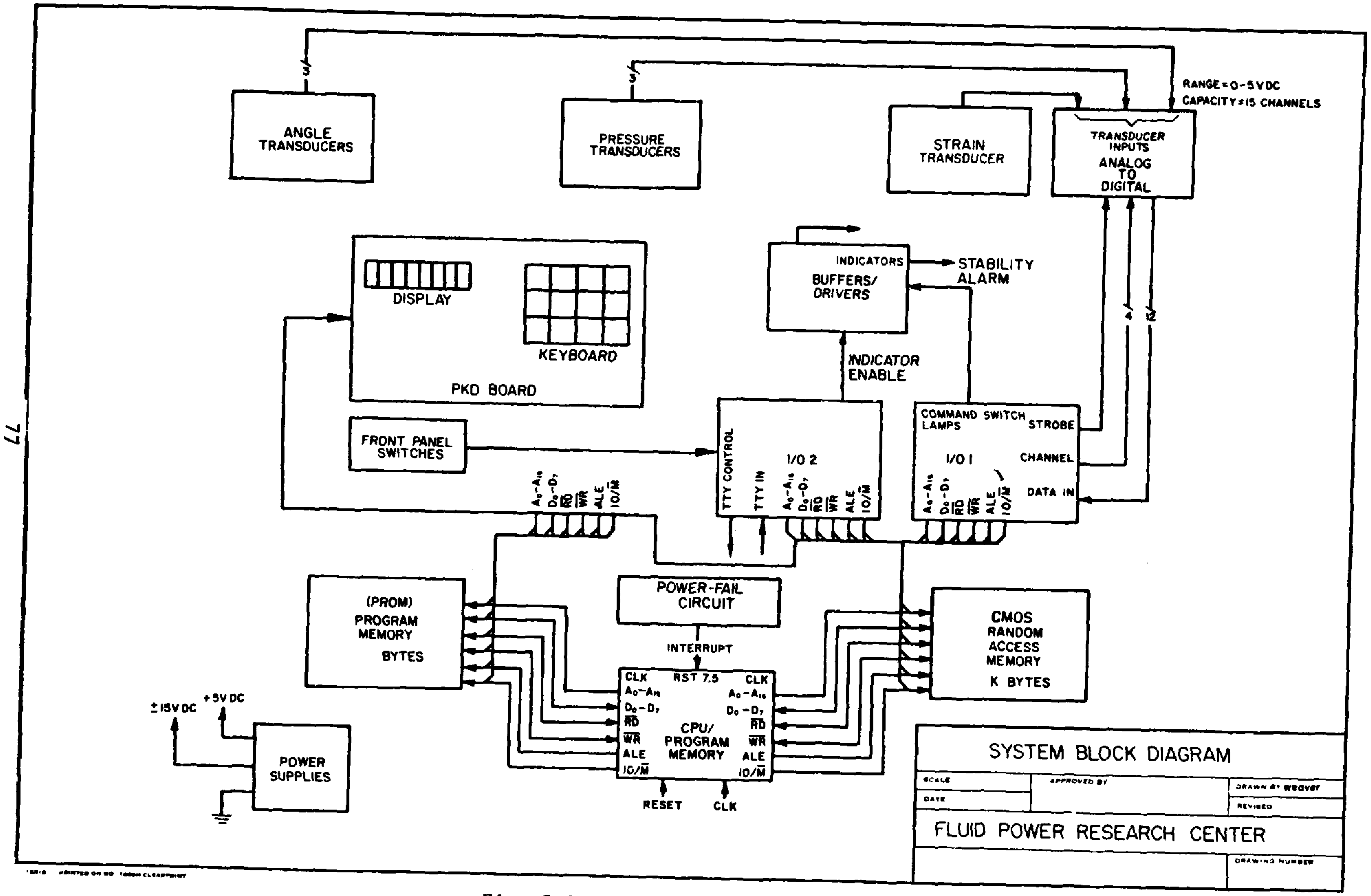


Fig. 5-1 System Block Diagram

measure 15 analog inputs, which are then converted to engineering units. When an analog input is measured, it is assigned a symbolic name and can be referenced similar to any other variable.

Communications with the operator are through a 16-key numeric keyboard and 10 digit L.E.D. display. The operator has the capability of entering parametric data from this keyboard, or reading data stored in CMOS RAM. He can also halt the currently executing procedure from the front-panel.

All the cards (except Keyboard/Display) are contained in two eight-slot card racks and interconnect via the backplane "motherboards" and multiconductor flat cable. The entire enclosure is fabricated using a modular concept to facilitate repair. The following paragraphs provide a detailed explanation of each circuit.

CENTRAL PROCESSING UNIT

The CPU-EPROM card contains both the 8085 μP and a portion of FP/1 Interpreter, which resides in EPROM.

The CPU executes 8085 machine operations stored as binary instructions in Read-Only-Memory, performing sequential logic operations at a 3MHz rate. Additional support circuitry performs the following functions:

a) 8212 address latch to demultiplex the 8085 bus

b) 8205 address decoder for 2716 addressing

c) 8216 bidirectional buffers to prevent bus loading

d) 74LS244 and 74LS368 tri-state drivers for control signals

ERASEABLE PROGRAMMABLE READ-ONLY MEMORY

The EPROM section is populated by 4 Intel 2716 devices. These are 2K byte (high density) Erasable Programmable Read Only Memories for storing the programming language, as well as the Stability Monitor software. They can be erased by exposure to ultraviolet radiation and then reprogrammed, if desired.

CMOS RANDOM ACCESS MEMORY

The CMOS RAM provides the system with limited non-volatile read/write memory capability to store the vehicle parameters, stability limits, and other system constants. The FP/1 interpreter also uses CMOS RAM for "scratch-pad" and variable storage.

The memory devices used are Intel 5101L-1 450 nsec., static, CMOS RAM's. The CMOS technology makes possible the long battery life required to hold parametric information when system power is disconnected. The decoding circuit consists of A1 and A4 together with a 3205 and 8212 latch. The 74LS30, A1, A2 and 74LS244 perform data bus enabling and driving. An on-board battery with transistor switching network is used to automatically switch from vehicle to battery power. Power failure is sensed by the CA3130 comparator circuit which disables CMOS RAM to protect its contents and generates an interrupt to the μP.

PROGRAMMABLE PERIPHERAL INTERFACE

The I/O cards provide the digital input/output interface to the μC. The device used is the Intel 8255 PPI, which is directly compatible with the 8085 and requires a minimum amount of support circuitry - one 8205 address decoder. All digital inputs and control outputs are routed through the I/O card. The specific configuration of these lines is software programmable.

KEYBOARD/DISPLAY

This board resides on the front-panel of the Stability Monitor enclosure and provides both keyboard inputs (parameter changes and identification) and visual output via the on-board 16-key pad and 10 digit L.E.D. display.

The primary component is the 8279 Programmable Keyboard Display device, which controls the keyboard parsing and display refresh actions. An oscillator circuit (555 Timer) provides the correct refresh clock rate. The segment driver circuit (9374, 2N2907's) and the digit driver circuit (U4, U5, U6, U7, U8, 7442) are activated from the PKD. The keyboard parsing is performed via the 7442 decoder and PKD Scan/return lines.

ANALOG - TO - DIGITAL CONVERTER

The A/D incorporated in the Monitor is an entire 16 channel, 12-bit data acquisition system in a single module and resides on one printed circuit board. The unit (SDM 853) is produced by Burr-Brown Corporation. The A/D analog input range is 0.0 to 5.0

volts. The output is a digitized linear response from 0000_{16} to FFF_{16} (0_{10} to 4095_{10}), e.g., a 2.5 v input should yield an output of $7FF_{16}$ (2047_{10}), or mid-scale. The channel number is received and latched via the STROBE control line which also causes a conversion to begin after the appropriate multiplexer has accessed the analog input line. The instrumentation amplifier then feeds the Sample-and-Hold which prevents "signal droop" at the A/D converter input. The 12 outputs are routed through an I/O card to the CPU. Conversion time is 24 μ sec.

SIGNAL CONDITIONING

An 8-channel signal conditioning card provides the appropriate signal level conversion and filtering from the transducer outputs to the A/D input. Thus the analog signals are converted to the appropriate 0-5v range for A/D conversion. Each channel consists of two stages. Stage 1 is configured as a standard differential amplifier and stage two provides gain and offset capability.

POWER SYSTEM

Power for the microcomputer is generated by the two power supplies residing on the rear panel. The 12v D.C. vehicle power is fused (6 Amperes) and filtered to prevent RFI transient noise from entering the system. The power supplies generate +5 volts D.C. @ 6 Amps for the digital circuitry and $\pm$ 15 volts D.C. @ 0.3 Amps for the analog circuits. All power cables are routed through "molex" style connectors to enhance the modular concept. The +15

volt regulator contains an integral over-voltage protection (OVP) device to protect circuitry in the event of power supply failure. Exact power supply electrical schematics appear in the appendix. The D.C. input operating range is 9.8v minimum, and 18.0v maximum.

FRONT AND REAR PANELS

Three toggle-type switches are provided for operator inputs, as system commands. A ten-digit display indicates the parameter values stored in CMOS RAM, and the keyboard allows specifying the parameter. A key-type power switch is installed on the front panel, and 3 L.E.D.'s show instability about the respective axis.

The vehicle transducer interface is at the rear panel where the power and analog connectors reside. Shielded cabling is used to route analog input signals to the Monitor. A connector for the teletype (TTY) is also provided on the rear panel, but is not used. The Audio Alert is also present here. The appendix contains all schematics for the panels.

TRANSDUCERS

There are seven transducers providing analog information to the Monitor regarding the load and vehicle orientation in 3-space. See the appendix for calibration and connection information.

Pressure Transducers: these provide information regarding the load.

Pressure 1 (P1) - SER NO. 46 - rod side of tilt cylinder; 0-3000 psi
Pressure 2 (P2) - SER NO. 47 - head side of tilt cylinder; 0-3000 psi
Pressure 3 (P3) - SER NO. 48 - lift cylinder pressure; 0-3000 psi

These are National Semiconductor transducers with a high level output, requiring +15v excitation.

Angle Transducers: these determine vehicle orientation.

Angle 1 (P4) - angle made from x-axis; (-45° to +45°)
Angle 2 (P5) - angle made from y-axis; (-45° to +45°)
Angle 3 (P6) - mast angle (from vertical); (-45° to +45°)

These are Humphrey pendulum type transducers.

Strain Link: this strain gauge transducer (LEBOW) provides side loading information (i.e. unbalanced load) Strain (P7) - (-250 μstrain to +250 μstrain).

SYSTEM OUTPUTS

The Stability Monitor outputs are provided for the WFT operator and the test engineer. Two different types of alarms are controlled by digital type outputs, i.e. on/off. These outputs are:

Digital Output	Alarm*
SV1	Left Roll Indicator
SV2	Pitch Axis Indicator
SV3	Right Roll Indicator

* If any one of the three indicators is activated, the Audio Alert will sound.

The 3 indicators reside on the system front panel and show instability about the respective axia. The Audio Alert is located on the rear panel. These digital outputs are activated by the FP/1 <u>SET</u> instruction, and deactivated by the <u>RESET</u> instruction.

CHAPTER VI

TESTING PROGRAM

A testing program was performed on the WFT STABILITY MONITOR to verify its operation and examine the performance of the device. The tests were conducted on a Clark Model 1641076 (Serial No. RT 115) warehouse lift truck. The vehicle is a 4000 pound cushion-tire lift truck.

Tests performed include lifting a load in excess of the rated capacity of the vehicle, tilting the mast with rated load, and operation on various slopes. All tests were performed under static conditions using a dead load suspended from the forks similar to that discussed in ANSI B56.1-1975 with the exception that the load is suspended from directly on the top face of the forks.

TESTING PROGRAM

The tests performed were as follows:

Test 1 - Lift a Load in Excess of Rated Capacity

A 2000 kgm (4500 pound force) load is lifted with the mast at a height of 1.8V (6.0 ft.) with the mast vertical, and the vehicle on a horizontal surface. The three Stability Indices are recorded.

The above procedure is repeated for a total of 5 repetitions.

Test 2 - Tilt the Mast with the Rated Load.

A 1800 kgm (4000 pound force) load is lifted at heights of

AD-A088 551 OKLAHOMA STATE UNIV STILLWATER FLUID POWER RESEARCH --ETC F/6 13/3
SECOND GENERATION LOAD STABILITY SENSOR DEVICE.(U)
MAY 80 E C FITCH, R L DECKER, M T YOKLEY DAAK70-78-C-0067

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2.44, 3.0, 3.6 M (8, 10, 12 ft.) and with mast angles of $+2^{o}$ (forward), 0^{o} (vertical and -2^{o} (rearward). The Stability Indices are recorded for each test condition. Each is repeated five times. (Note: The procedure of tilting the mast and then lifting to the specified height has been used to insure more accurate measurement of test conditions.) (Note: During this test, care was taken to insure that the tilt cylinder was neither fully extended nor fully retracted in order. As discussed in previous chapters, such a condition would result in erroneous results).

Test 3 - Lift a Load on a Longitudinal Slope.

Lift a 900 kgm (2000 pound force) load at a height 2.4 M (8.0 ft.) with the vehicle positioned on a 4^{o} longitudinal slope (rear wheels elevated above front wheels. Record the Stability Indices and repeat for a total of five repetitions.

Test 4 - Lift a Load on a Lateral (Side) Slope.

Lift a 900 kgm (2000 pound force) load at a height of 1.8 M (6.0 ft.) with the vehicle positioned on a 6^{o} (operator's left side lower) lateral slope. Record the Stability Indices and repeat for a total of five repetitions.

Test 5 - Lift a Load on a Combination Slope.

Lift an 8900 kgm (2000 pound force) load at a height of 1.8

CHAPTER VI

TESTING PROGRAM

A testing program was performed on the WFT STABILITY MONITOR to verify its operation and examine the performance of the device. The tests were conducted on a Clark Model 1641076 (Serial No. RT 115) warehouse lift truck. The vehicle is a 4000 pound cushion-tire lift truck.

Tests performed include lifting a load in excess of the rated capacity of the vehicle, tilting the mast with rated load, and operation on various slopes. All tests were performed under static conditions using a dead load suspended from the forks similar to that discussed in ANSI B56.1-1975 with the exception that the load is suspended from directly on the top face of the forks.

TESTING PROGRAM

The tests performed were as follows:

Test 1 - Lift a Load in Excess of Rated Capacity

A 2000 kgm (4500 pound force) load is lifted with the mast at a height of 1.8V (6.0 ft.) with the mast vertical, and the vehicle on a horizontal surface.

The three Stability Indices are recorded.

The above procedure is repeated for a total of 5 repetitions.

Test 2 - Tilt the Mast with the Rated Load.

A 1800 kgm (4000 pound force) load is lifted at heights of

M (6.0 ft.) with the vehicle positioned on a side slope of 9° (operator's right side lower) and forward slope of 1°. Record the Stability Indices and repeat for a total of five repetitions.

RESULTS

It should be readily apparent that numerous physical constants must be specified to describe the vehicle geometry and the performance of the system is greatly affected by the exact numerical constants chosen. Although these constants provide great flexibility in adapting the system to various vehicle geometries, the task of accurately determining all of the constants is indeed non-trivial. Many of the constants can be readily determined by direct measurement. But several are difficult to accurately measure. These are best determined by trial-and-error procedures. Numerous tests were performed to gain insight in the behavior of the system and to tailor the system performance. The constants actually used for the testing program are shown in Fig. 6-1.

During the tests, a significant problem was identified. The sensitivity analysis was used to identify which (if any) of the input parameters had little effect on the overall performance of the system. It was found that all parameters must be measured and these measurements must be incorporated in the calculations. But the analysis did not address in depth the reverse question, that is, which parameters have a dominant or even overwhelming effect on the performance

of the system. After extensive testing, it was realized that one parameter in particular had a very tremendous effect on the system.

The strain measured via the strain link has a highly dominant effect on the left and right roll stability indices. Unfortunately, numerous instrumentation problems were encountered in trying to accurately measure the desired strain. The instrumentation problems have been determined to result from two sources. First, drift in the signal conditioning electronics resulted in erroneous measured values. The signal conditioning electronics was redesigned to lessen this drift. Second, the strain link appears to exhibit an offset in its output signal after just a few cycles. It is not known whether this is an historesis effect on the strain link or if the mechanical installation is experiencing permanent deformation during the tests.

This instrumentation problem is complicated by the fact that the strain must be measured is very small in magnitude. This small-magnitude value has a very substantial effect on the actual stability values. To appreciate the significance of this, refer to the test results as shown in Tables 6-1 through 6-14. The theory predicts that S_{LR} and S_{RR} should be equal when the vehicle is operated on level surface and the load is supported equally by both forks. Table 6-1 shows the results obtained with the vehicle unloaded on level surface. The instrumentation was zeroed prior to initiating this test and the two roll Stability Indices were equal and the values obtained for all three Stability Indices were very close to that predicted by theory. But once the tests were initiated (for example refer to Table 6-2) the

Parameter	Equation Variable	Representation	Metric Value	Units
P10	Y_v	Y component; c.g. vector	-0.7493	Meters
P11	Z_v	Z component; c.g. vector	0.6426	Meters
P16	Z_m	Z component, Mast vector	0.4318	Meters
P17	Z_T	Z component, Tilt cylinder vector	0.5588	Meters
P19	X_m	X component, Mast vector	0.9493	Meters
P20	λ_{LRX}		-0.2735	------
P21	λ_{LRY}	Direction cosines for Left roll axis	0.9527	------
P22	λ_{LRZ}		-0.1323	------
P23	A_2	Tilt cylinder piston area (head side)	.0235	Meters^2
P24	A_1	Tilt cylinder piston area (rod side)	.01707	Meters^2
P25	A Lift	Lift cylinder piston area	.0025	Meters^2
P26	Y_T	Y component of Tilt cylinder position	-0.5969	Meters
P27	K	Scaling factor for σ	1.371703×10^2	N-m/$\mu\sigma$
P28	W_m	Mast weight(stationary)	3620.0	Newtons
P29	P_{R2X}	Position (x component) to Reaction Froce	0.8000	Meters
P30	X_v	X component, c.g. Pos. Vector	0.4000	Meters
P31	W_v	Weight of vehicle (Less Mast)	24715.3	Newtons
P41	λ_{RRX}		0.2735	-------
P42	λ_{RRY}	Direction cosines for Right Roll Axis	0.9527	-------

Table 6-1

Geometric Parameter Values for Testing Program

Parameter	Equation Variable	Representation	Metric Value	Units
P43	λ_{RRZ}		-0.1323	-----
P44	----	$A_{Pitch\ Limit}$	1000.0	Newton-Meter
P45	----	$S_{LR\ Limit}$	800.0	Newton-Meters
P46	----	$S_{RR\ Limit}$	800.0	Newton-Meter

Table 6-1 (Continued)

TEST RESULTS

Test ___________

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_p (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	0	0	0	0	0	17573	6012	5958
2	0	0	0	0	0	17535	6022	5969
3	0	0	0	0	0	17544	5954	6033
4	0	0	0	0	0	17611	5954	5996
5	0	0	0	0	0	17630	5949	5991
					Average	17600	5980	5990
					Coef of Variance*	0.2	0.1	0.1
					Theoretical	18500	4400	4400
					Percent Diff*	-5.0	6.3	6.3

$$\text{Coef of Variance} = \frac{\overline{S}}{\text{Full Scale}} \times 100$$

$\overline{S}$ = Sample Standard Deviation

Full Scale = 18000 for S_p

25000 for S_{LR}, S_{RR}

$$\text{Percent Diff} = \frac{\text{Average-Theoretical}}{\text{Full Scale}} \times 100$$

Table 6-1 No-Load Test Results

TEST RESULTS

Test #1

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N–M)	S_{LR} (N–M)	S_{RR} (N–M)
1	1.83m (6 ft)	2000 KGM	0	0	0	3145	25183	14283
2	"	"	0	0	0	3089	25402	14598
3	"	"	0	0	0	2937	25547	13686
4	"	"	0	0	0	2353	26000	13993
5	"	"	0	0	0	3277	25320	14074
					Average	2960	25500	14100
					Coef of Variance	2.0	1.2	1.4
					Theoretical	4520	15800	15800
					Percent Diff	-8.7	38.8	-6.8

Table 6-2 Level Surface - 2000 Kgm Test

TEST RESULTS

Test 2-A1

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	2.4M (8 ft)	1800 Kgm (4000 lb)	2^{o} (Back)	0^{o}	0	5332	20080	15829
2	"	"	"	"	"	5054	21754	14404
3	"	"	"	"	"	5641	22935	13556
4	"	"	"	"	"	5424	21999	13763
5	"	"	"	"	"	5437	21265	14462
					Average	5380	21600	14400
					Coef of Variance	1.2	4.2	3.6
					Theoretical	7410	16300	16300
					Percent Diff	-8.1	29.4	-10.6

Table 6-3 Level Surface - 2.4M Mast Back 2^{o}

TEST RESULTS

Test 2-A2

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	2.4M (8 ft)	1800 Kgm (4000 lb)	0	0	0	3100	20300	15763
2	"	"	"	"	"	2379	21354	16080
3	"	"	"	"	"	2608	21765	15731
4	"	"	"	"	"	3038	20642	16407
5	"	"	"	"	"	3073	21331	15477
					Average	2840	21100	15900
					Coef of Variance	1.8	2.4	1.5
					Theoretical	6030	16700	16700
					Percent Diff	-12.8	24.4	4.4

Table 6-4 Level Surface - 2.4M-Mast Vertical

TEST RESULTS

Test 2-A3

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_p (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	2.4M (8 ft)	1800 Kgm (4000lb)	2^o (Forward)	0	0	2656	19752	17178
2	"	"	"	"	"	2750	19914	15808
3	"	"	"	"	"	2823	20245	17691
4	"	"	"	"	"	2301	20540	16778
5	"	"	"	"	"	3090	20691	17272
					Average	2720	20200	16900
					Coef of Variance	1.6	1.6	2.8
					Theoretical	4650	17100	17100
					Percent Diff	-7.7	17.2	-1.1

Table 6-5 Level Surface - 2.4M-Mast Forward 2^o

TEST RESULTS

Test 2-B1

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	3.0M (10 ft)	1800 Kgm (4000lb)	2^{o} (Back)	0	0	3955	23015	12974
2	"	"	"	"	"	4588	22902	13914
3	"	"	"	"	"	4403	23843	13209
4	"	"	"	"	"	4147	23462	12836
5	"	"	"	"	"	4383	22488	14479
					Average	4300	23100	13500
					Coef of Variance	1.4	2.1	2.8
					Theoretical	7790	16200	16200
					Percent Diff	-14.0	38.3	-15.0

Table 6-6 Level Surface - 3M - Mast 2^{o} Back

TEST RESULTS

Test 2-B2

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	3.0M (10 ft)	1800 Kgm (4000lb)	0	0	0	2284	22106	14037
2	"	"	"	"	"	3368	23181	15592
3	"	"	"	"	"	2862	22054	14708
4	"	"	"	"	"	1670	23336	15038
5	"	"	"	"	"	2909	22296	15025
					Average	2620	22600	14900
					Coef of Variance	3.6	2.5	2.2
					Theoretical	6030	16700	16700
					Percent Diff	-13.6	32.8	-10.0

Table 6-7 Level Surface - 3M - Mast Vertical

TEST RESULTS

Test 2-B3

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	3.0M (10 ft)	1800 Kgm (4000 lb)	2^{o} (Forward)	0	0	1592	22465	14461
2	"	"	"	"	"	1663	22048	14733
3	"	"	"	"	"	1703	23058	15750
4	"	"	"	"	"	1400	21591	15229
5	"	"	"	"	"	1101	23214	15288
					Average	1490	22500	15100
					Coef of Variance	1.4	2.7	2.0
					Theoretical	4270	17200	17200
					Percent Diff	-11.1	29.4	-11.7

Table 6-8 - Level Surface - 3M - Mast 2^{o} Forward

TEST RESULTS

Test 2-C1

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_p (N–M)	S_{LR} (N–M)	S_{RR} (N–M)
1	3.7M (12 ft)	1800 Kgm (4000lb)	2° Back	0	0	3828	19685	16623
2	"	"	"	"	"	4368	21499	18276
3	"	"	"	"	"	4707	19361	16620
4	"	"	"	"	"	4935	19901	17533
5	"	"	"	"	"	4785	19280	18112
					Average	4520	19900	17400
					Coef of Variance	2.5	3.6	3.1
					Theoretical	8170	16100	16100
					Percent Diff	-14.6	21.1	7.2

Table 6-9 - Level Surface - 3.7M - Mast Back 2°

TEST RESULTS

Test 2-C2

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_p (N–M)	S_{LR} (N–M)	S_{RR} (N–M)
1	3.7M (12 ft)	1800 Kgm (4000lb)	0	0	0	2003	19430	17011
2	"	"	"	"	"	2092	20921	17675
3	"	"	"	"	"	3611	24119	20812
4	"	"	"	"	"	3116	24111	20822
5	"	"	"	"	"	2947	25552	20319
					Average	2750	22800	19300
					Coef of Variance	3.8	10.2	7.3
					Theoretical	6030	16700	16700
					Percent Diff	-13.1	33.9	14.4

Table 6-10 Level Surface - 3.7M - Mast Vertical

TEST RESULTS

Test 2-C3

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	3.7M (12 ft)	1800 Kgm (4000lb)	2^o (Forward)	0	0	203	24464	20215
2	"	"	"	"	"	251	22113	19355
3	"	"	"	"	"	458	24742	20518
4	"	"	"	"	"	197	24231	20119
5	"	"	"	"	"	839	24590	20882
					Average	390	24000	20200
					Coef of Variance	1.5	4.3	2.3
					Theoretical	3900	17300	17300
					Percent Diff	-14.0	37.2	16.1

Table 6-11 Level Surface - 3.7M - Mast Forward 2^o

TEST RESULTS

Test #3

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	2.4M (8 ft)	900 Kgm (2000lbs)	0	0	4^o (Forward)	8013	14502	12437
2	"	"	"	"	"	8001	14905	12549
3	"	"	"	"	"	8001	14813	12467
4	"	"	"	"	"	8284	14763	12362
5	"	"	"	"	"	7874	15008	12560
					Average	8030	14800	12500
					Coef of Variance	0.6	1.0	0.5
					Theoretical	9780	10800	10800
					Percent Diff	-7.0	22.2	9.4

Table 6-12 Test on 4^o Forward Slope

TEST RESULTS

Test #4

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_p (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	1.8M (6 ft)	900 Kgm (2000lb)	0	6^o Lift	0	10305	7564	15524
2	"	"	"	"	"	10456	7467	15636
3	"	"	"	"	"	9836	7624	15712
4	"	"	"	"	"	10521	7228	15785
5	"	"	"	"	"	10622	7262	16030
					Average	10300	7430	15700
					Coef of Variance	1.7	0.7	0.7
					Theoretical	12300	6200	12300
					Percent Diff	11.1	4.9	13.6

Table 6-13 Test on 6^o Side Slope

TEST RESULTS

Test #5

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	1.8M (6 ft)	900 Kgm (2000lb)	0	9° Right	1° Back	10493	23788	2111
2	"	"	"	"	"	11152	24076	1801
3	"	"	"	"	"	10651	21348	1388
4	"	"	"	"	"	10374	22127	1070
5	"	"	"	"	"	10726	22414	1394
					Average	10700	22800	1550
					Coef of Variance	1.7	4.5	1.6
					Theoretical	12700	14300	1710
					Percent Diff	-8.0	47.2	-0.9

Table 6-14 Test on Combination Slope

measured stability index for the left roll was vastly different than the one for the right roll and did not agree with theory. Throughout the remaining tests this number was consistently approximately 40% higher whereas the right stability index agreed quite closely to theory. Although it is not shown with these test results, if the test whose results were shown in Table 6-1 were repeated at the end of the testing, this offset in the left stability index would certainly be observed.

Although the test results presented here show an offset in the left stability index, it is not believed that the problem is strictly confined to this index. Similarly, offsets could occur which result in poor performance in the right stability index.

The results of the testing program are shown in Tables 6-1 through 6-14. The statistical variation as measured by the Coefficient of Variance is typically quite small. (Note that the Coefficient of Variance has been defined to be the variance of the values obtained normalized by the full scale reading. Therefore, the coefficient of variants can be interpreted as the variance expressed as percent of full scale).

The accuracy of data obtained (ignoring S_{LR}) is generally between 10-15% of that predicted by theory. Considering the complexity of this system, approximations using the theory, and measurement uncertainty, this is probably an acceptable accuracy.

An interesting study is to assume that the data shown for Test 2 was actually taken with the vehicle on a 2^{o} forward incline. The rationale here is to understand the effect of an offset in the transducer

which measures the vehicle forward angle. The results are shown in Tables 6-15 through 6-23. Note that with only very minor exceptions the values obtained for S_P and S_{RR} are extremely accurate.

TEST RESULTS

Test 2-A1*

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	2.4M (8 ft)	1800 Kgm (4000lb)	2^o (Back)	0	2^o*	5332	20080	15829
2	"	"	"	"	"	5054	21754	14404
3	"	"	"	"	"	5641	22935	13556
4	"	"	"	"	"	5424	21999	13763
5	"	"	"	"	"	5437	21265	14462
					Average	5380	21600	14400
					Coef of Variance	1.2	4.2	3.6
					Theoretical	5470	14700	14700
					Percent Diff	0.5	38.3	-1.7

*Assumed

Table 6-15 Test 2-A1 with Assume Operating Conditions

TEST RESULTS

Test 2-A1

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_p (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	2.4M (8 ft)	1800 Kgm (4000lb)	0	0	2*	3100	20300	15763
2	"	"	"	"	"	2379	21354	16080
3	"	"	"	"	"	2608	21765	15713
4	"	"	"	"	"	3038	20642	16407
5	"	"	"	"	"	3073	21331	15477
					Average	2840	21100	15900
					Coef of Variance	1.8	2.4	1.5
					Theoretical	4090	15100	15100
					Percent Diff	-5.0	33.3	4.4

*Assumed

Table 6-16 Test 2-A2 with Assume Operating Conditions

TEST RESULTS

Test ____________

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	2.4M (8 ft)	1800 Kgm (4000lb)	2° (Forward)	0	2*	2656	19752	17178
2	"	"	"	"	"	2750	19914	15808
3	"	"	"	"	"	2823	20245	17691
4	"	"	"	"	"	2301	20540	16778
5	"	"	"	"	"	3090	20691	17272
					Average	2720	20200	16900
					Coef of Variance	1.6	1.6	2.8
					Theoretical	2710	15500	15500
					Percent Diff	0	26.1	7.8

*Assumed

Table 6-17 Test 2-A3 With Assumed Operating Conditions

TEST RESULTS

Test ___________

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_p (N–M)	S_{LR} (N–M)	S_{RR} (N–M)
1	3.0M (10 ft)	1800 Kgm (4000lb)	2^o Back	0	2*	3955	23015	12974
2	"	"	"	"	"	4588	22902	13914
3	"	"	"	"	"	4403	23843	13209
4	"	"	"	"	"	4147	23462	12836
5	"	"	"	"	"	4383	22488	14479
					Average	4300	23100	13500
					Coef of Variance	1.4	2.1	2.8
					Theoretical	5470	14700	14700
					Percent Diff	-4.7	46.7	-6.7

*Assumed

Table 6-18 Test 2-B1 with Assumed Operating Conditions

TEST RESULTS

Test ____________

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	3.0M (10ft)	1800Kgm (4000lb)	0^o	0^o	2*	2284	22106	14037
2	"	"	"	"	"	3368	23181	15592
3	"	"	"	"	"	2862	22054	14708
4	"	"	"	"	"	1670	23336	15038
5	"	"	"	"	"	2909	22296	15025
					Average	2620	22600	14900
					Coef of Variance	3.6	2.5	2.2
					Theoretical	3710	15200	15200
					Percent Diff	-4.4	41.1	-1.7

Table 6-19 Test 2-B2 with Assumed Operating Conditions

TEST RESULTS

Test 2-A2

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_p (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	3.0M (10ft)	1800Kgm (4000lb)	2° Forward	0°	2*	1592	22465	14461
2	"	"	"	"		1663	22048	14733
3	"	"	"	"	"	1703	23058	15750
4	"	"	"	"	"	1400	21591	15229
5	"	"	"	"	"	1101	23214	15288
					Average	1490	22500	15100
					Coef of Variance	1.4	2.7	2.0
					Theoretical	1950	15700	15700
					Percent Diff	-1.8	37.8	-3.3

Table 6-20 Test 2-B3 with Assumed Operating Conditions

TEST RESULTS

Test 2-A3

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_p (N–M)	S_{LR} (N–M)	S_{RR} (N–M)
1	3.7M (12ft)	1800Kgm (4000lb)	2^o Back	0^o	2*	3828	19685	16623
2	"	"	"	"	"	4368	21499	18276
3	"	"	"	"	"	4707	19361	16620
4	"	"	"	"	"	4935	19901	17533
5	"	"	"	"	"	4785	19280	18112
					Average	4520	19900	17400
					Coef of Variance	2.5	3.6	3.1
					Theoretical	5470	14700	14700
					Percent Diff	-3.8	28.8	15.0

Table 6-21 Test 2-C1 with Assumed Operating Conditions

TEST RESULTS

Test ____________

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_p (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	3.7M (12ft)	1800Kgm (4000lb)	0°	0°	2*	2003	19430	17011
2	"	"	"	"	"	2092	20921	17675
3	"	"	"	"	"	3611	24119	20812
4	"	"	"	"	"	3116	24111	20822
5	"	"	"	"	"	2947	25552	20319
					Average	2750	22800	19300
					Coef of Variance	3.8	10.2	7.3
					Theoretical	3330	15300	15300
					Percent Diff	-2.3	41.7	22.2

Table 6-22 Test 2-C2 with Assumed Operating Conditions

TEST RESULTS

Test ____________

	Load Condition		Vehicle Conditions			Stability Index		
	Mast Height (meters)	Load Mass (kgm)	Mast Angle (degrees)	Side Angle (degrees)	Forward Angle (degrees)	S_P (N-M)	S_{LR} (N-M)	S_{RR} (N-M)
1	3.7M (12ft)	1800Kgm (4000lb)	2^o Forward	0^o	2*	203	24464	20215
2	"	"	"	"	"	251	22113	19355
3	"	"	"	"	"	458	24742	20518
4	"	"	"	"	"	197	24231	20119
5	"	"	"	"	"	839	24590	20882
					Average	390	24000	20200
					Coef of Variance	1.5	4.3	2.3
					Theoretical	1190	15900	15900
					Percent Diff	-3.2	45.0	23.9

Table 6-23 Test 2-C3 with Assumed Operating Conditions

TEST RESULT CONCLUSIONS

By examining the trends exhibited in the data shown in this chapter, it is concluded that the monitor can indeed detect vehicle stability. But, very accurate, reliable, and precise measurements in instrumentation techniques <u>must</u> be used. The difference of two degrees in the angle measured by the vehicle forward angle sensor represents only approximately 2% of full scale. Yet this 2% variation could result in substantially different results as illustrated in the data shown in Tables 6-15 through 6-23.

As previously discussed, it was learned through experience that the accurate measurement of the strain value is highly critical in obtaining acceptable results.

CHAPTER VII

SUMMARY CONCLUSIONS AND RECOMMENDATIONS

This report has studied the Stability Index (S.I.) for counter-balanced type vehicles operating under dynamic conditions on nonhorizontal surfaces. The equations applicable to conventional warehouse lift trucks were developed using this theory. Then, restrictions on these equations were imposed to consider only static operation on nonhorizontal surfaces. The relative imporatnce of the various terms was studied using a sensitivity analysis approach.

An exploratory system was developed which implements the S.I. Theory on warehouse lift trucks operating under static conditions. The system utilizes a microcomputer to measure various perimeters and calculate an estimate of the relative stability using the Stability Index. Provisions were made in this device to allow for easy modification of geometric perimeters and for the examination of intermediate results.

A testing program was conducted on the device operating on horizontal surfaces. It was found in this program that reasonable correlation was obtained between the predicted stability and the actual stability.

It is concluded that the S.I. Theory is a valid concept. As suggested in the introduction to this report, a critical need exists to augment the operators ability and judgement for safer vehicles. The Stability Index Theory provides a means of assimilating available information and using this to predict stability on a real time basis. Although the computations required can be quite complex, this is little problem for modern, state of the art microcomputers.

But, several problems still do exist. Mechanical stops on the hydraulic cylinders of many vehicles can result in inferring erroneous information. Although limit switches can be installed to detect when such a situation arises, a better approach would be to utilize cylinders with hydraulic stops. Then the pressure transducers would be installed directly into the chamber of a cylinder with the confined fluid and would provide valid information at all times. Although retro-fitting existing vehicles with set cylinders may be somewhat expensive, it is quite reasonable to assume that new machines could be ordered with such cylinders.

Another problem area is that of the transducers. Two factors are of concern. First, the cost of the devices--especially when 6 transducers are used--can be a significant part of the total system cost. Because of the general increase of the use of electronics and microcomputers, it is expected that the transducers cost will significantly decrease over the next few years. The second aspect to the transducer problem is the ruggedness of these devices. Although devices such as pressure transducers have in the past been considered to be quite delicate, the prevalent use of these in the automotive industry is expected to greatly improve this situation. But, it can not be overemphasized that the concept in its present form necessitates very good instrumentation techniques. Such techniques may not be reasonable for field implementations.

One final problem exists--the speed of reaction to dynamic conditions. This was discussed in Chapter 2.

It was pointed out that this represents a very fundamental hinderance to the successful realization of the stability monitoring concept in the field. Two approaches are possible to circumvent this problem. First, the dynamic equations developed in Chapter 2 could be implemented using appropriate accelerometer-type transducers. As pointed out in Chapter 2, it is not anticipated that such an approach will provide sufficient warning to the operator. A second approach would be to utilize the static equations similar to those developed in this study. In this situation stability limits which are sufficiently conservative to insure stability even in a dynamic situation would be imposed. It may be desirable to further augment the stability limits (by increasing them) as a function of operating factors such as vehicle speed. This approach would provide a warning to the operator that he is in a potentially dangerous situation whereas the former approach would warn the operator that he is indeed in a dangerous situation. It is believed that the latter approach is the better from both the stand point of the operator's safety and feasibility of implementation in the field.

It is recommended that further research be pursued to explore the operation of the system in dynamic situations. It is recommended that computer simulations be performed to analyze the behavior of the vehicle under dynamic conditions and stability predicitons using both the dynamic and static Stability Index models.

In summary, the Stability Index concept has been demonstrated to be a viable approach to improving vehicle stability. Although several problems are yet to be resolved, it is believed that if the various

problems can be adequately solved this concept may be feasible for field implementation on counterbalanced-type vehicles. Although this present work is concentrated primarily on warehouse lift trucks, it is quite reasonable to believe that the approach can be readily expanded to accomodate other front loading-type of material handling equipment such as rough terrain lift trucks.

APPENDIX A

THE FP/1 LANGUAGE

APPENDIX A

The FP/1 Language

Fluid Power/1 (FP/1) is a computer language developed by the Fluid Power Research Center at Oklahoma State University for controlling fluid power systems. Operations commonly required for automating these systems have been identified; and single-statement, high-level commands have been defined for implementing these operations. FP/1 has been tailored for hydraulic test stand control. Other applications for this language include mobile equipment control and data acquisition in the fluid power environment.

FP/1 was designed in order to allow a hydraulic test engineer to learn to program the system with very little training. The language has been patterned after a well-known computer language--Basic. Its similarities with Basic enhance the ease of learning programming techniques. A knowledge of computers is *not* prerequisite to the efficient use of FP/1. FP/1 allows the use of a low-cost microcomputer system to perform tasks which were not previously economically feasible.

The high-level instructions in FP/1 vastly reduce the amount of time required for developing a program. Previous systems have been programmed in Assembly language. Experience has shown that, to develop such a program, from one-half to one and one-half years are required. Any subsequent changes must be made in Assembly language.

It was the goal for the Fluid Power Research Center in developing FP/1 to allow test programs to be programmed in as short as one day, following also for future changes to be made with a minimum of time and effort.

Additional statements have been incorporated into FP/1 to facilitate its utilization in the Stability Monitor. Table A-1 summarized the FP/1 instructions and provides a description of each of these.

Table A-1 FP/1 Instruction Summary

Actuator Group:	
SET	Form: SET SVn Sets Digital line n.
RESET	Form: RESET SVn Resets digital line n.
Measurement Group:	
MEAS	Form: MEAS parameter. Measures test parameters in engineering units. Includes pressures, temperatures, flows. Results stored until next measurement.
Program Control Group:	
FOR-NEXT	Form: FOR v = n1 TO n2 STEP n3. NEXT v. Program loops from FOR statement to NEXT statement. The loop parameter (v) is initialized to n1 and incremented by n3 when NEXT statement is encountered. Looping continues until v exceeds n2.
GO TO n	Program control transferred to line number n.
STOP	Halts execution.
END	End of program.
IF-THEN	Form: IF exp1 operator exp 2 THEN n.

Table A-1 (continued)

	The value of expl is compared to the value of exp 2. If relationship of these is as specified by operator, then program control is transferred to line number n. If relationship is not true, control passes to next statement. Valid operators are as follows:
	= Equal
	< Less than
	<= Less than or equal
	> Greater than
	>= Greater than or equal
	<> Not equal
GOSUB	Form: GOSUB n.
	Jump to subroutine located at n.
RETURN	Form: RETURN.
	Returns from Subroutine.
Arithmetic Group:	
LET	Form: LETvl = v2 opr v3.
	Performs specified operation (oper) onto v2 and v3. Results are stored in vl. Valid operators are as follows.
	+ Add
	- Subtract

Table A-1 (continued)

	* Multiply
	/ Divide
	v2 may be optionally prefixed by a minus sign.
Misc.:	
PRINT	Form: PRINT v1, v2, v3, etc.
	Outputs information onto teletype. Valid data types are variable or characters. Characters strings are enclosed in quotes.
DISPLAY	Form: DISPL
	The numeric data representing a system parameter (Pxx) are output to the system display.
REM	Form: REM "Characters."
	Inserts comments (remarks) in program listing.
Functions:	
SIN	Form: LET v1 = Sin Pn
	Sine of parameter Pn
	$0^{\circ} \leq Pn \leq 90^{\circ}$
COS	Form: LET v1 = Cos Pn
	Cosine of Parameter Pn
	$0^{\circ} \leq Pn \leq 90^{\circ}$
SQRT	Form: LET v1 = SQRT Pn
	Square root of Pn

APPENDIX B

CIRCUITS SCHEMATICS

and

WIRING LISTS

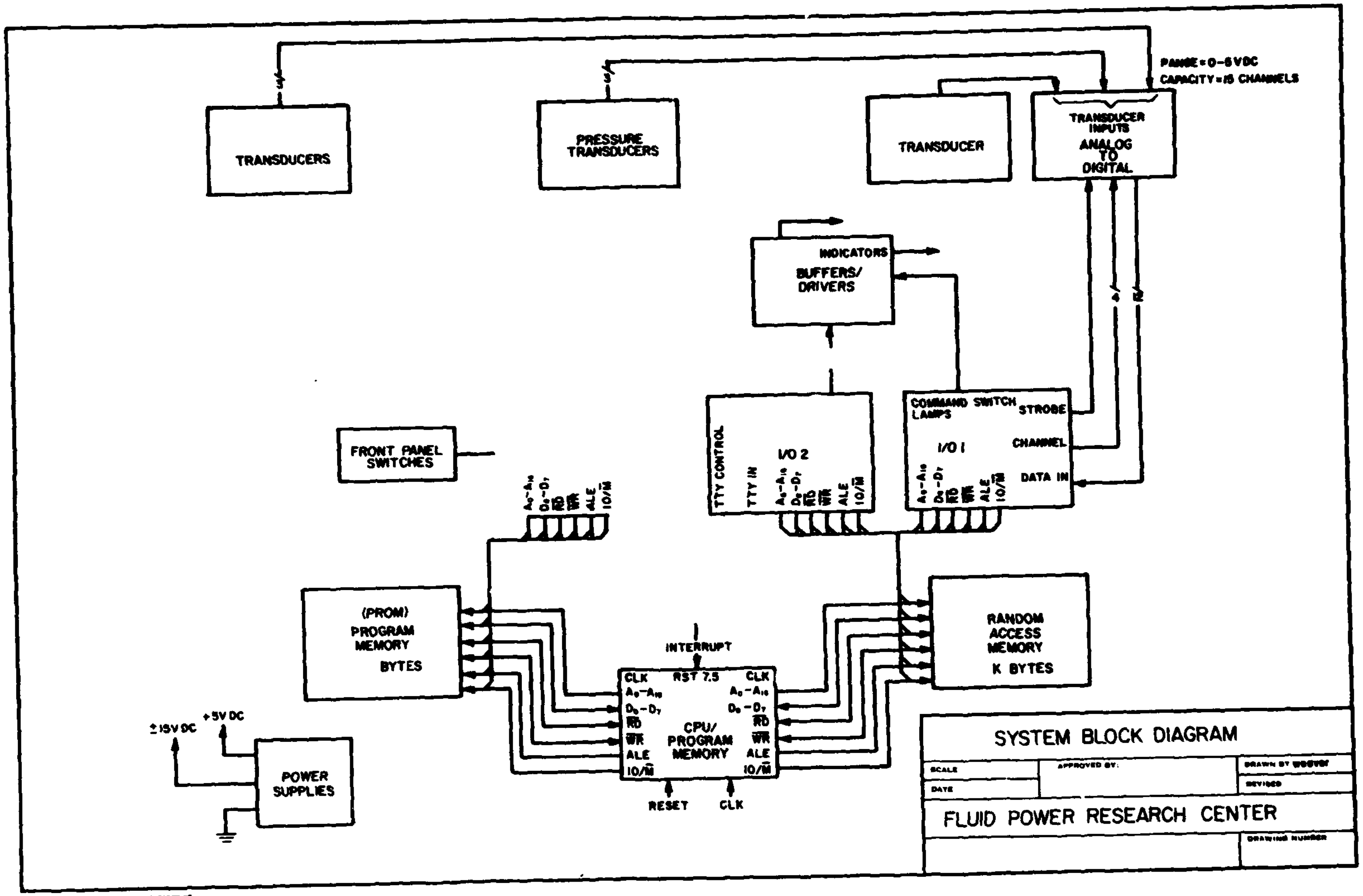


Fig. B-1 System Block Diagram

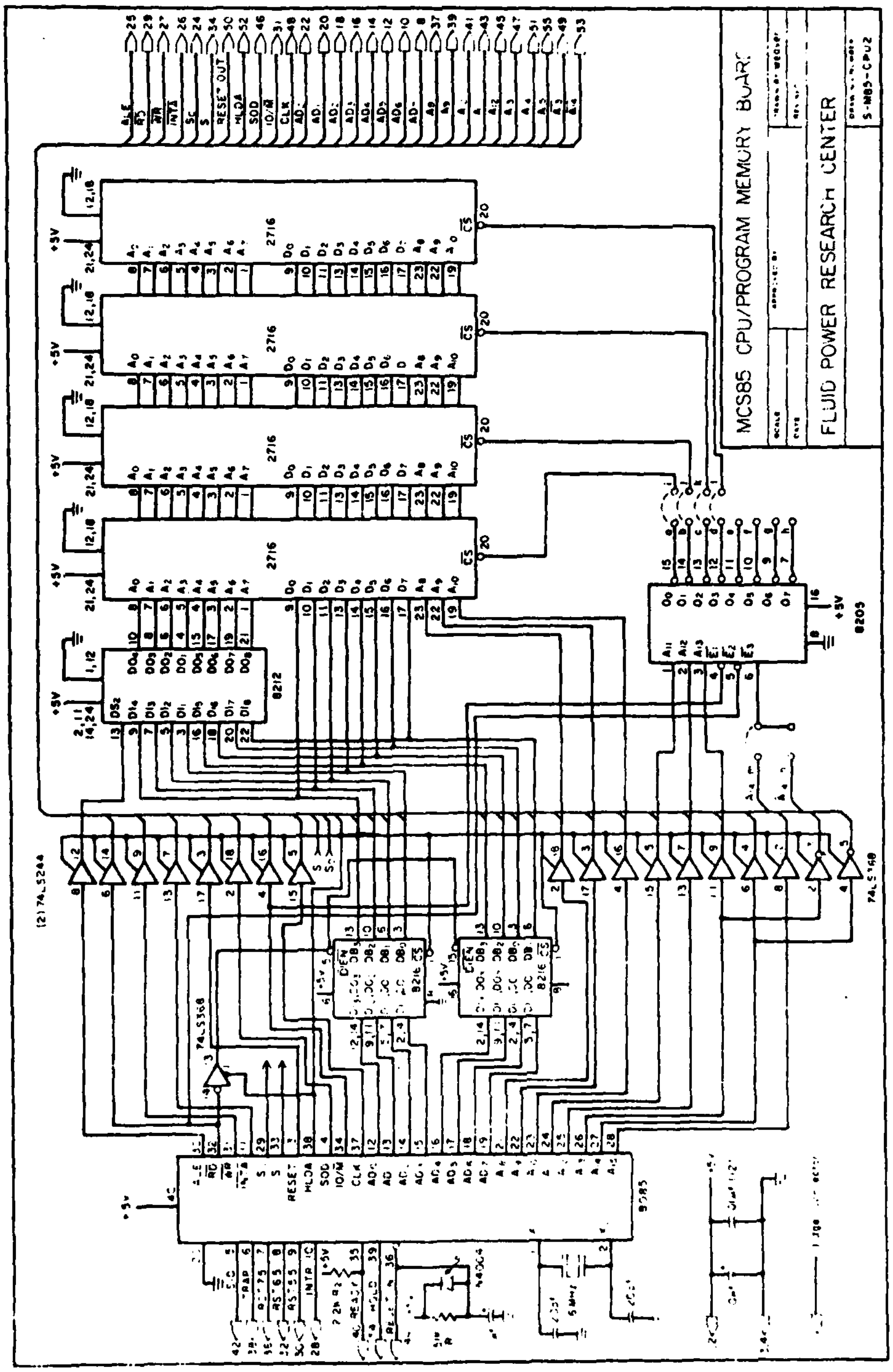


Fig. B-2 CPU/Program Memory Board Schematic

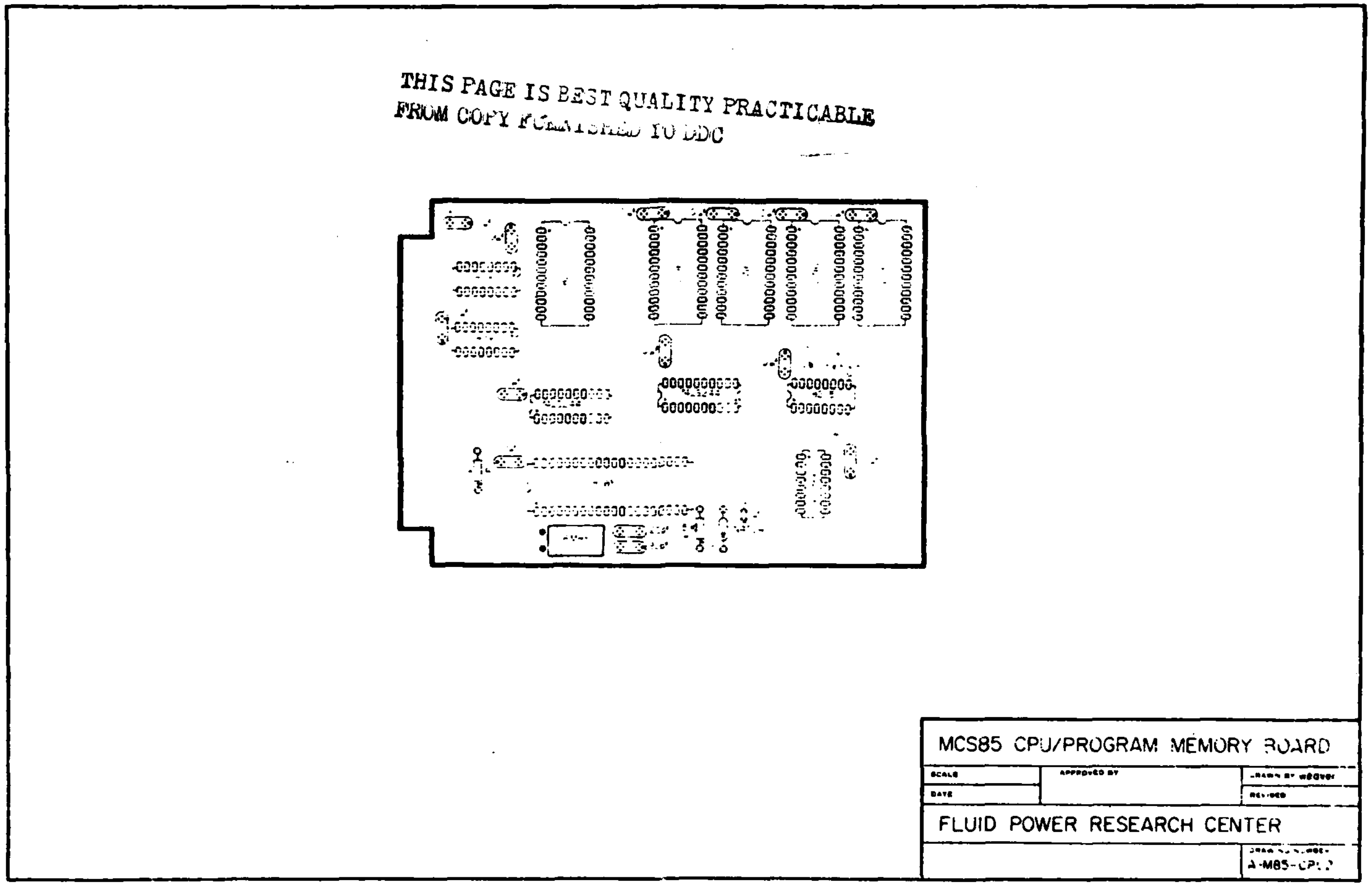
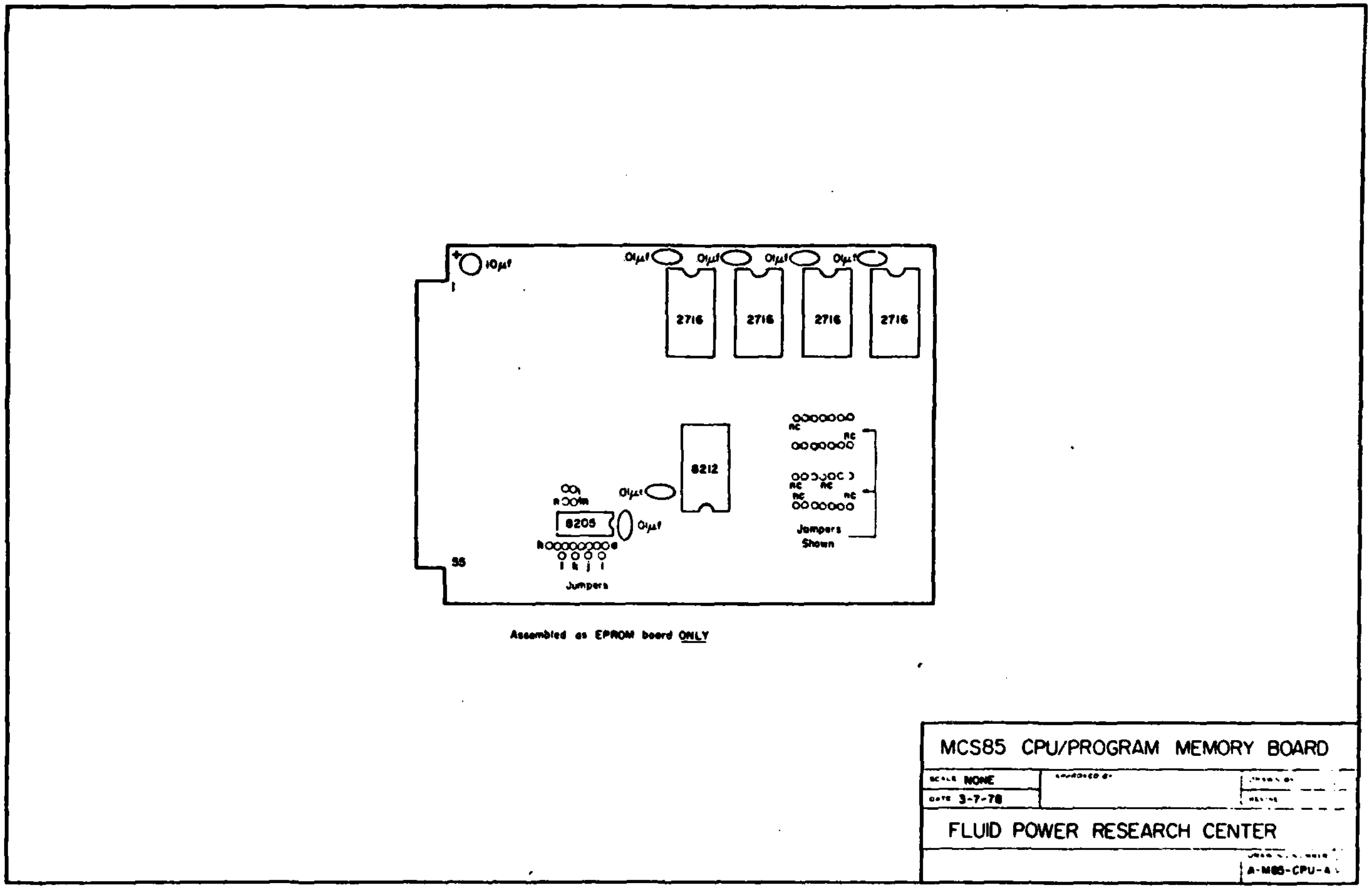


Fig. B-3 CPU/Board Assembly Drawing



B-4 Program Memory Assembly Drawing

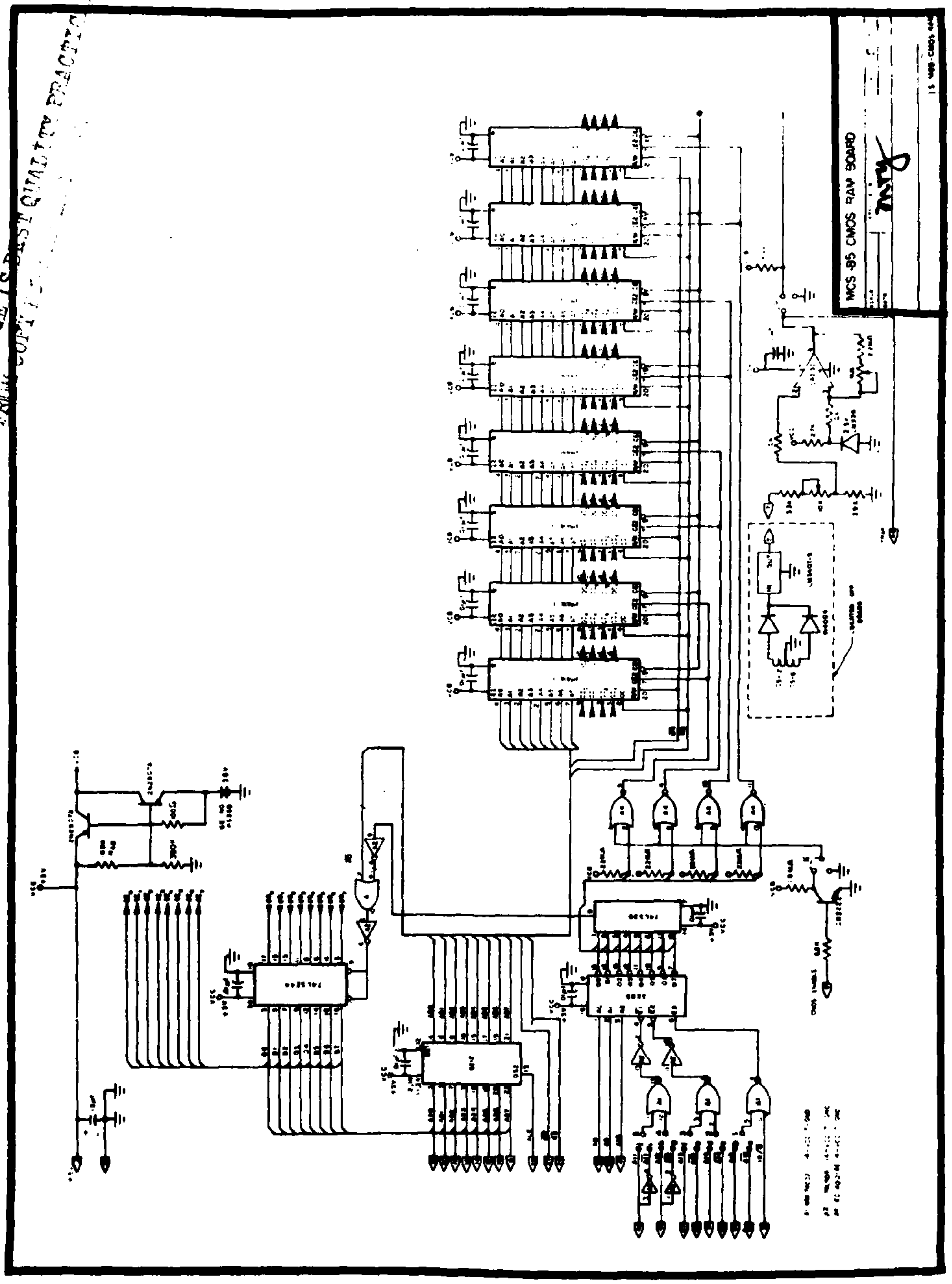


Fig. B-5 CMOS Board Schematic

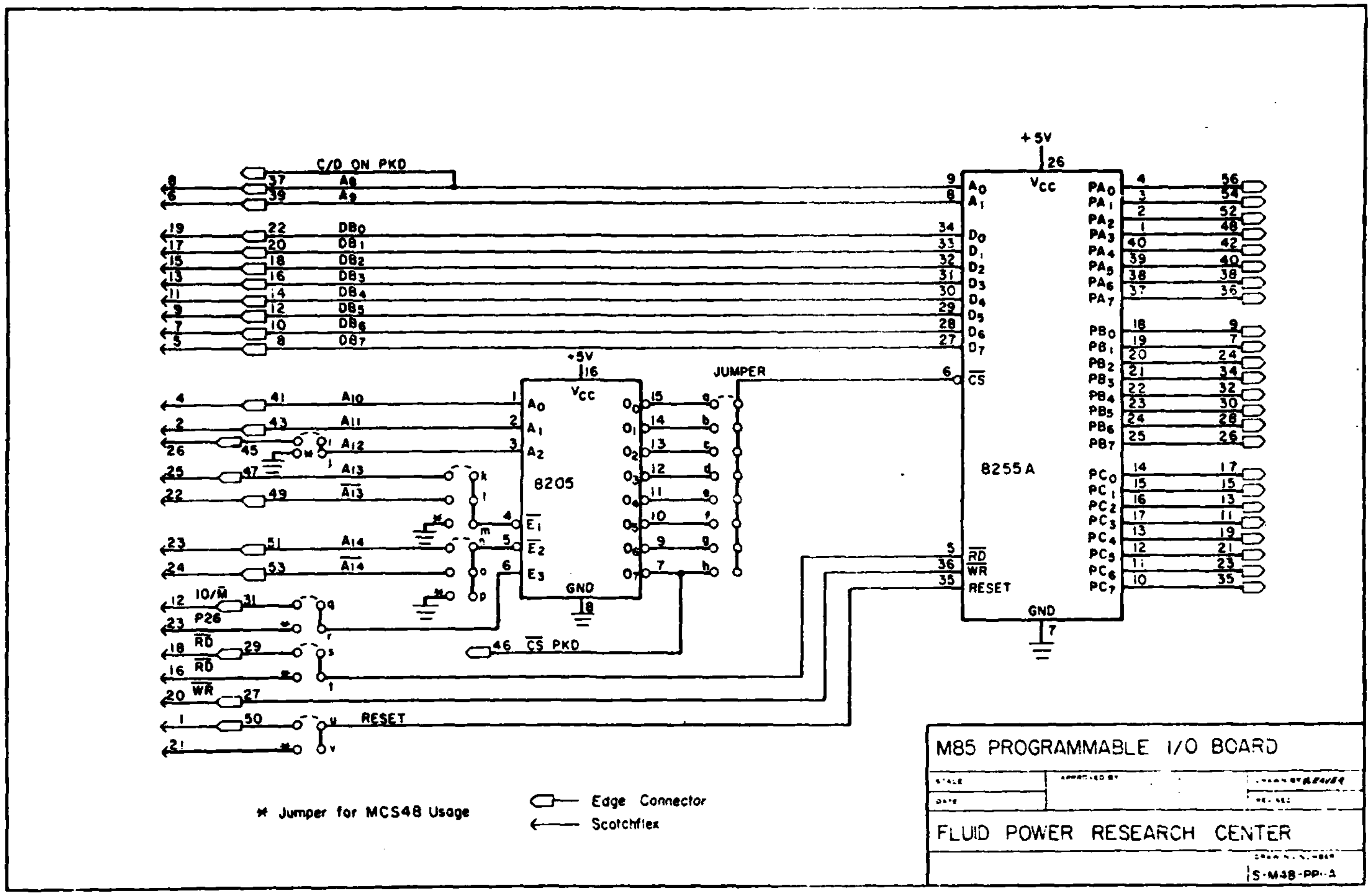


Fig. B-6 Programmable I/O Board Schematic

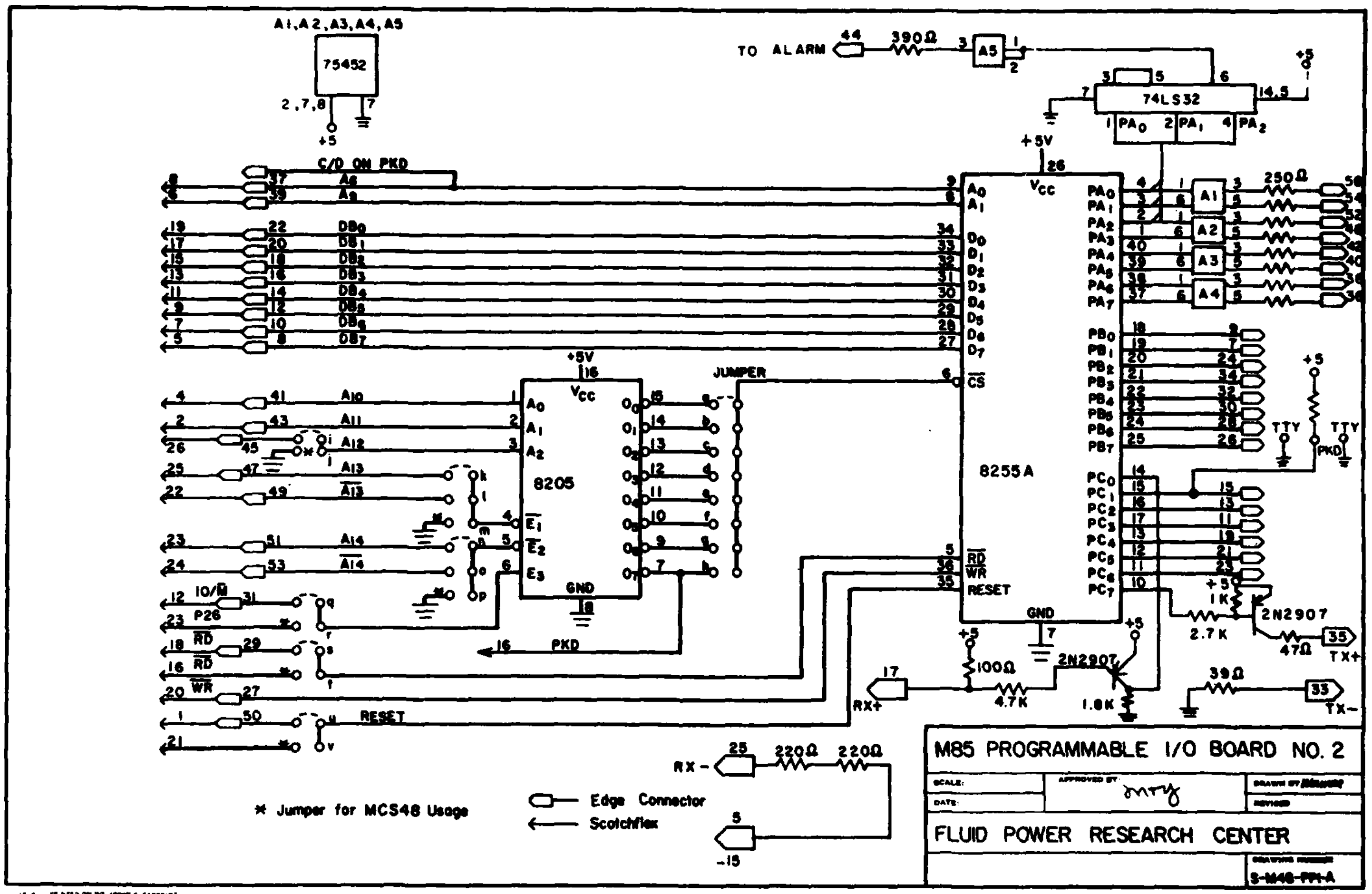


Fig. B-7 Programmable I/O Board No. 2 Schematic

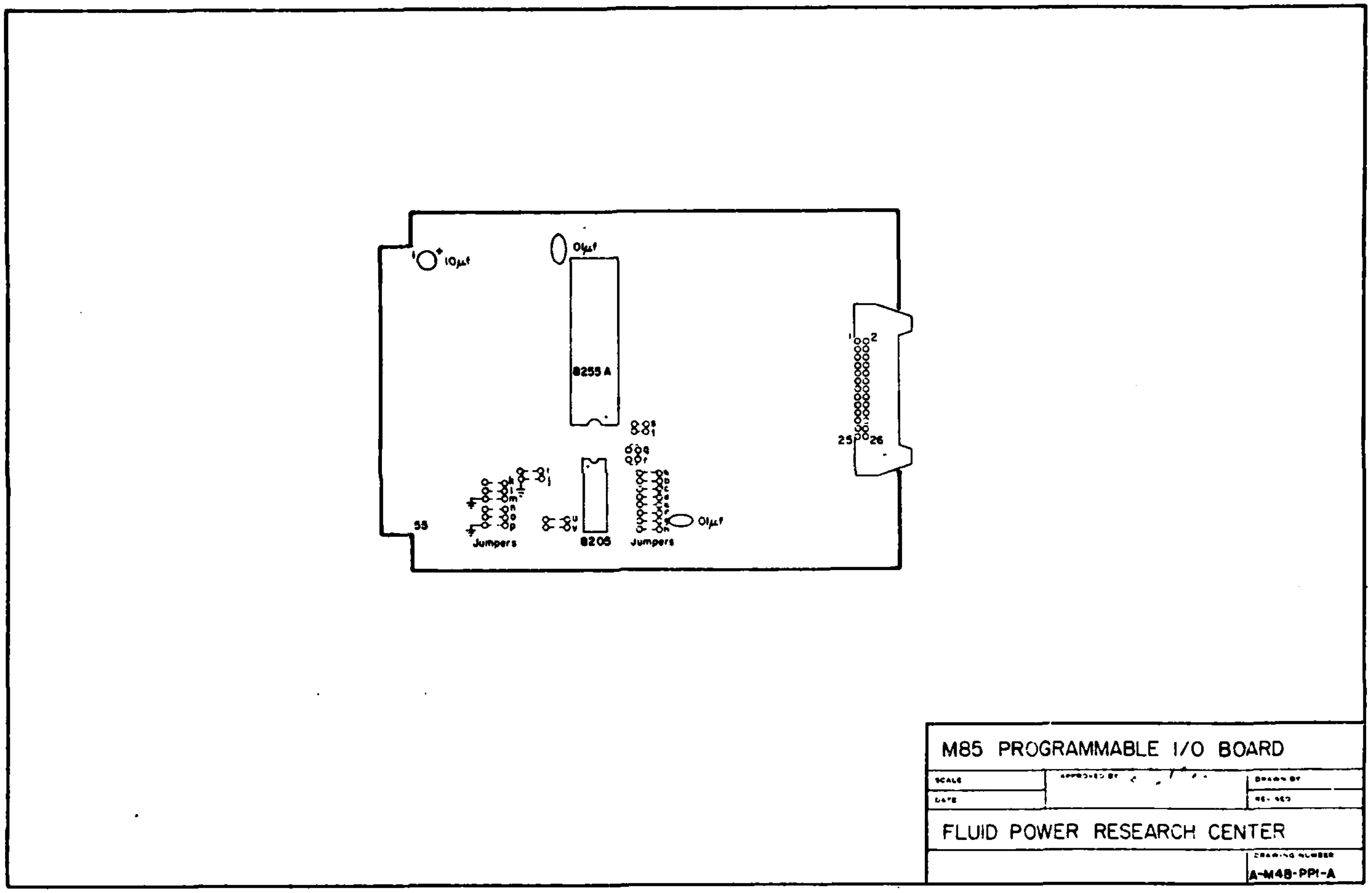


Fig. B-7 Programmable I/O Board Assembly Drawing

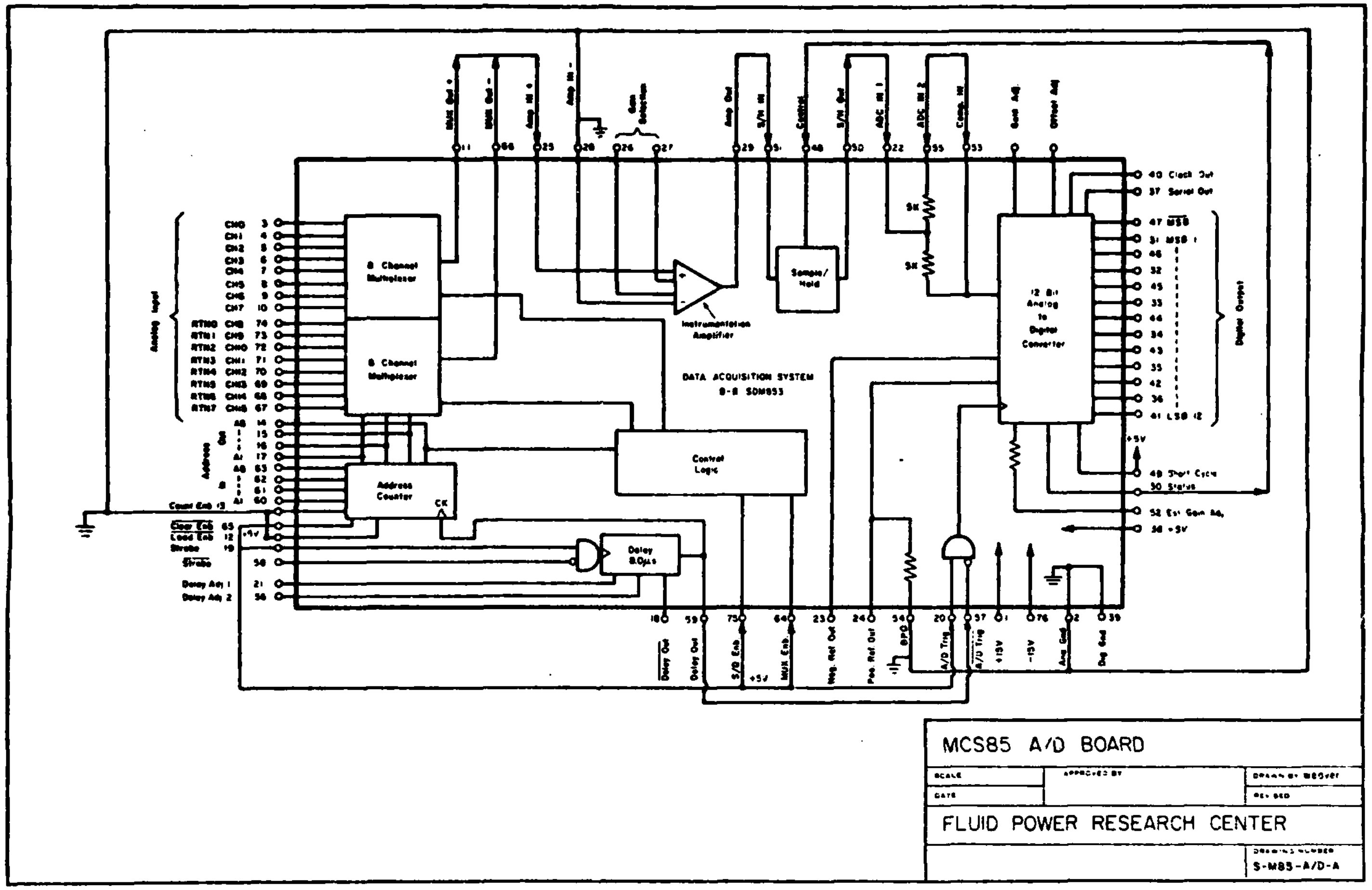


Fig. B-8 A/D Schematic

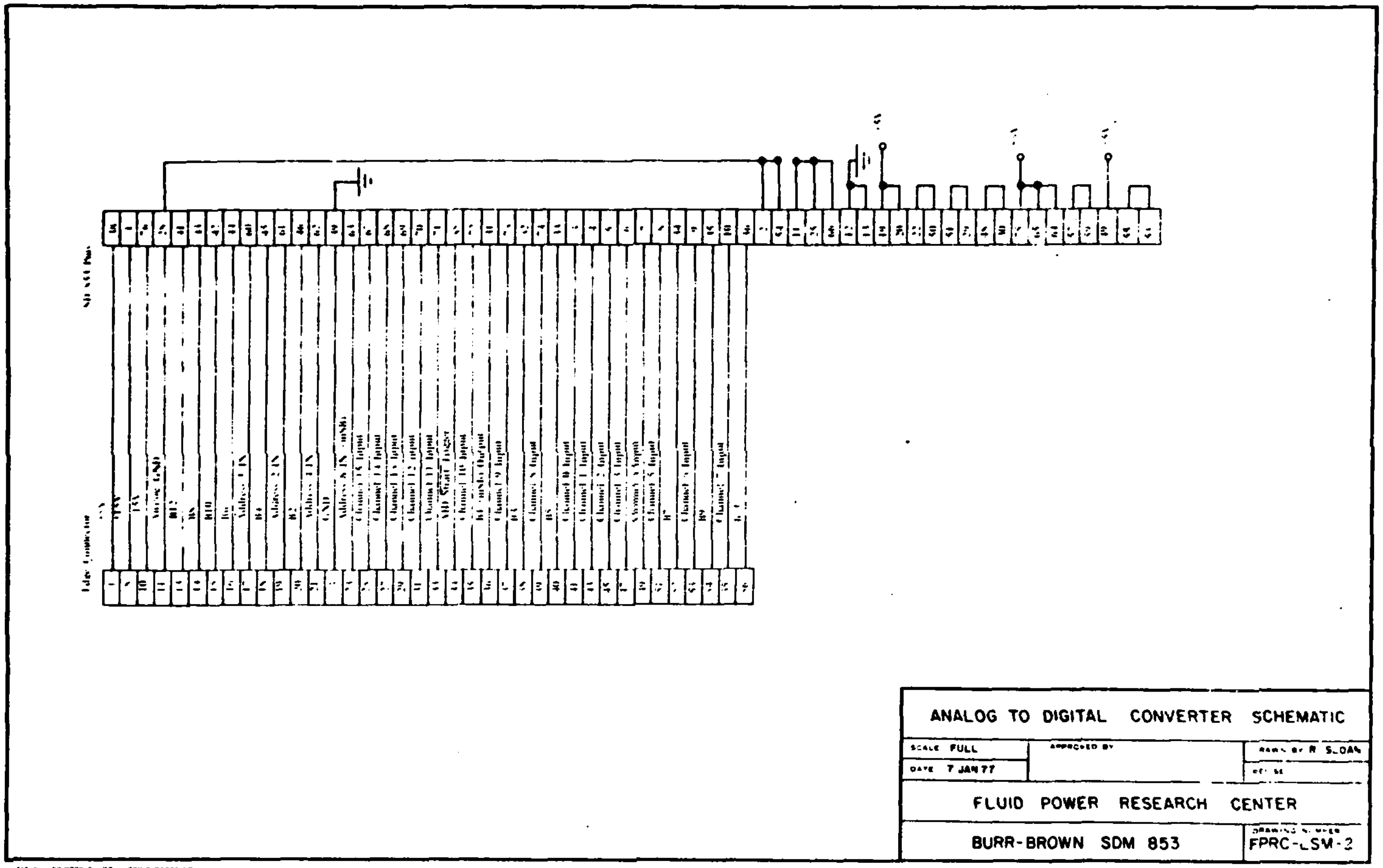
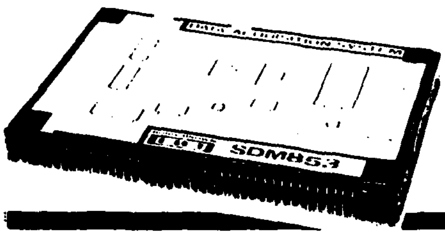


Fig. B-9 A/D Board Schematic

active filters/data conversion products

SDM853

active filters/data conversion products
amplifiers / DAC-ADC / multipliers-dividers
analog functions/modular power supplies
active filters/data conversion products
amplifiers / DAC-ADC / multipliers-dividers
analog functions/modular power supplies
active filters/data conversion products



DATA ACQUISITION SYSTEM

amplifiers / DAC-ADC / multipliers-dividers
analog functions/modular power supplies
active filters/data conversion products
amplifiers / DAC-ADC / multipliers-dividers
analog functions/modular power supplies
active filters/data conversion products
amplifiers / DAC-ADC / multipliers-dividers
analog functions/modular power supplies
active filters/data conversion products
amplifiers / DAC-ADC / multipliers-dividers
analog functions/modular power supplies
active filters/data conversion products
amplifiers / DAC-ADC / multipliers-dividers
analog functions/modular power supplies
active filters/data conversion products
amplifiers / DAC-ADC / multipliers-dividers
analog functions/modular power supplies
active filters/data conversion products
amplifiers / DAC-ADC / multipliers-dividers
analog functions/modular power supplies
active filters/data conversion products
amplifiers / DAC-ADC / multipliers-dividers
analog functions/modular power supplies

- SAVES DESIGN TIME
- RELIABLE – 168 hour bake
- LOW LEVEL or HIGH LEVEL INPUTS
- SAVES SPACE
- FLEXIBLE–Up to four modes of operation
- LOW COST– $170.00 in 100 quantities

DESCRIPTION

The SDM853 is a complete 8 or 16 channel data acquisition system in a compact 4.6" x 3.0" x 0.375" metal case. This system differs from most in that it can acquire and digitize low level or high level analog signals. A built-in high quality instrumentation amplifier allows input signal ranges of ±10mV to ±10V. This means that the SDM853 can be connected to low level sensors such as thermocouples and strain gauges without external signal conditioning.

This expandable module accepts either 16 single ended or 8 differential inputs and converts the multiplexed data signals into 12 bit digital words with an accuracy of ±0.025% at throughput rates of up to 33,000 samples per second.

BURR-BROWN

International Airport Industrial Park • P.O. Box 11400 • Tucson, Arizona 85734
Tel: 602-294-1431 • Twx: 910-952-1111 • Cable: BBRCORP • Telex: 66-6491

analog functions/modular power supplies

Fig. B-10 AD Data Sheet

SPECIFICATIONS

Typical at 25°C and rated power supplies unless otherwise noted

MODEL	SDM853
TRANSFER CHARACTERISTICS	
Throughput Rate (min)	30 kHz, 33 μsec/channel
Resolution	12 Bits
Number of Channels	16 single-ended/8 differential
ANALOG INPUTS	
ADC gain ranges	0-5V, 0-10V, ±2.5V, ±5V, ±10V
Amplifier gain range	1 to 1000
Amplifier gain equation	$G = 1 + 20\ k\Omega / R_{EXT}$[1]
Max. input voltage without damage	±16 volts
Max. input voltage for multiplexer operation	±10.24 volts
Input impedance	100 MΩ, 10 pF OFF Channel 100 MΩ, 100 pF ON Channel
Bias current	
25°C	20 nA
0°C to 70°C	50 nA
Differential Bias Current (25°C)	10 nA
Differential Bias Current Drift	0.1 nA/°C
Amplifier output noise (Gain = 100, R_s = 500Ω)	1.2 mV, rms, 7 mV, p-p
Amplifier input offset voltage (max)	400 μV
Amplifier voltage offset drift	$2 + \frac{20}{G}\ \mu V/°C$
ACCURACY(2)	
System RSS accuracy @ 25°C (Gain = 1)	±0.025% FSR[3] @ 30 kHz throughput
Linearity (Gain = 1)	±1/2 LSB, @ 30 kHz throughput
Differential linearity (Gain = 1)	±1/2 LSB, @ 30 kHz throughput
Quantizing error	±1/2 LSB
Gain error	Adjustable to Zero
Offset error	Adjustable to Zero
Power supply sensitivity	±0.005% FSR/% Change of supply voltage
STABILITY OVER TEMPERATURE	
System accuracy drift (max)	±30 ppm/°C of Reading
Linearity drift	±3 ppm of FSR/°C
DYNAMIC ACCURACY	
Sample & Hold aperture time	30 ns
Aperture time uncertainty	±5 ns
Error for full scale transition between successively addressed channels	1 LSB @ 30 kHz
Differential amplifier CMRR (Gain = 1)	74 dB @ 1kHz 65 dB @ 3kHz (100 dB @ 60 Hz Gain = 1000)
Channel cross talk	80 dB down @ 2 kHz, for OFF channel to ON channel
Sample & Hold feedthrough	80 dB down @ 5 kHz
Sample & Hold decay rate	10 μV/μs
OUTPUT	
Output Coding (Complementary)	Unipolar Straight Binary, Bipolar Offset, Binary Two's Complement
Gain trim[4]	Adjustable to zero error
Offset trim[4]	Adjustable to zero error
A/D Conversion Time	24 μsec
Delay	9 μs nominal, externally adjustable from 5.5 μs to 14 μs[5]
POWER REQUIREMENTS	±15V ±3% @ +50 mA, 5 mV rms ripple -15V ±3% @ -75 mA, 5 mV rms ripple +5V ±5% @ +300 mA, 25 mV rms ripple
ENVIRONMENTAL	
Operating temperature	0°C to 70°C
Storage temperature	-25°C to +85°C
Relative humidity	95% noncondensing

(1) With R_{EXT} between pins 26 and 27.
(2) No missing codes guaranteed.
(3) FSR means *Full Scale Range*.
(4) Gain and Offset controls are located in the module. The adjustment ranges are ±0.1% FSR for Gain and ±0.1% FSR for Offset.
(5) Adjustable to 10 seconds with external capacitor.

Fig. B-10 AD Data Sheet (continued)

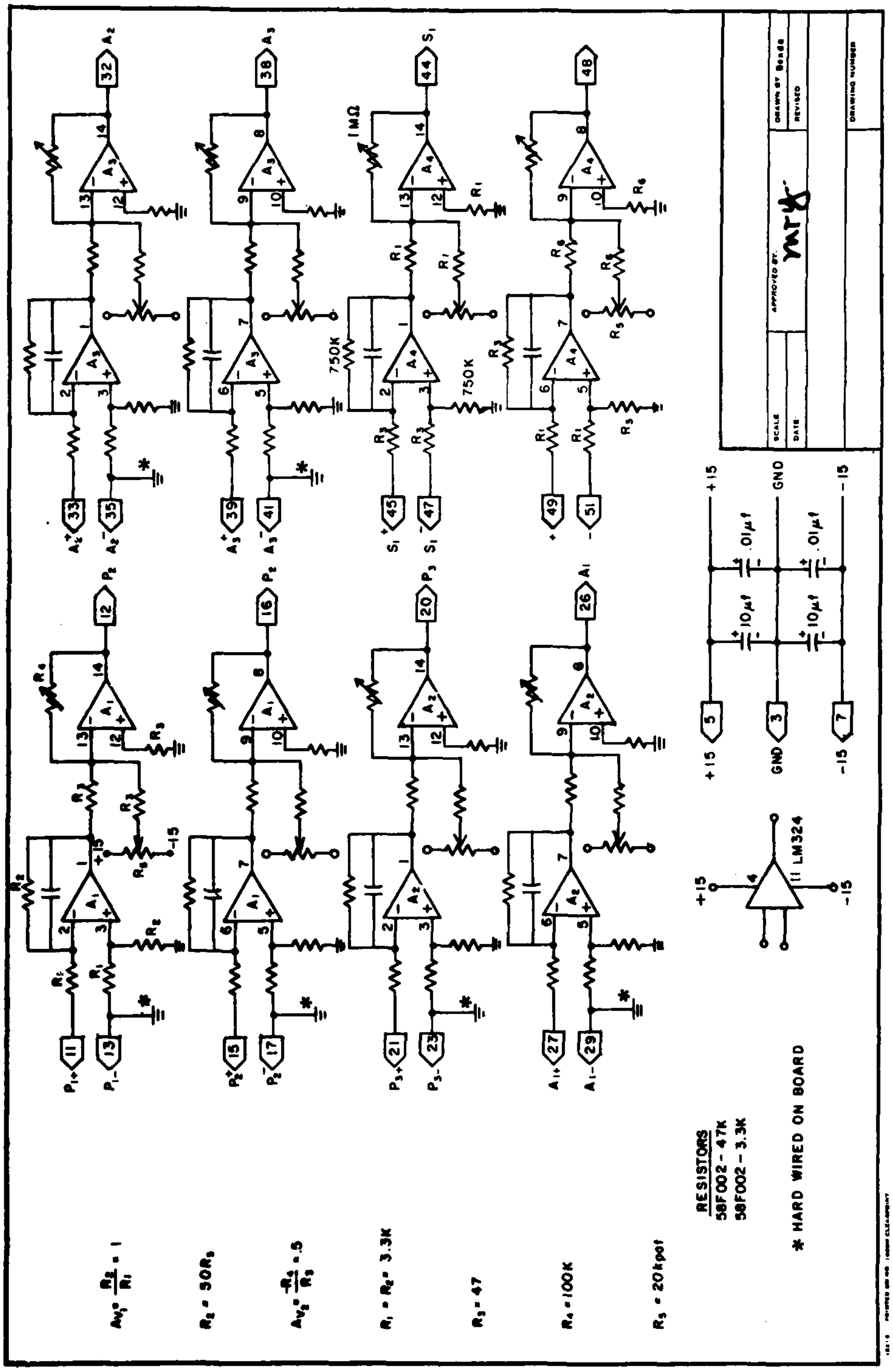


Fig. B-11 Signal Conditioning Schematic

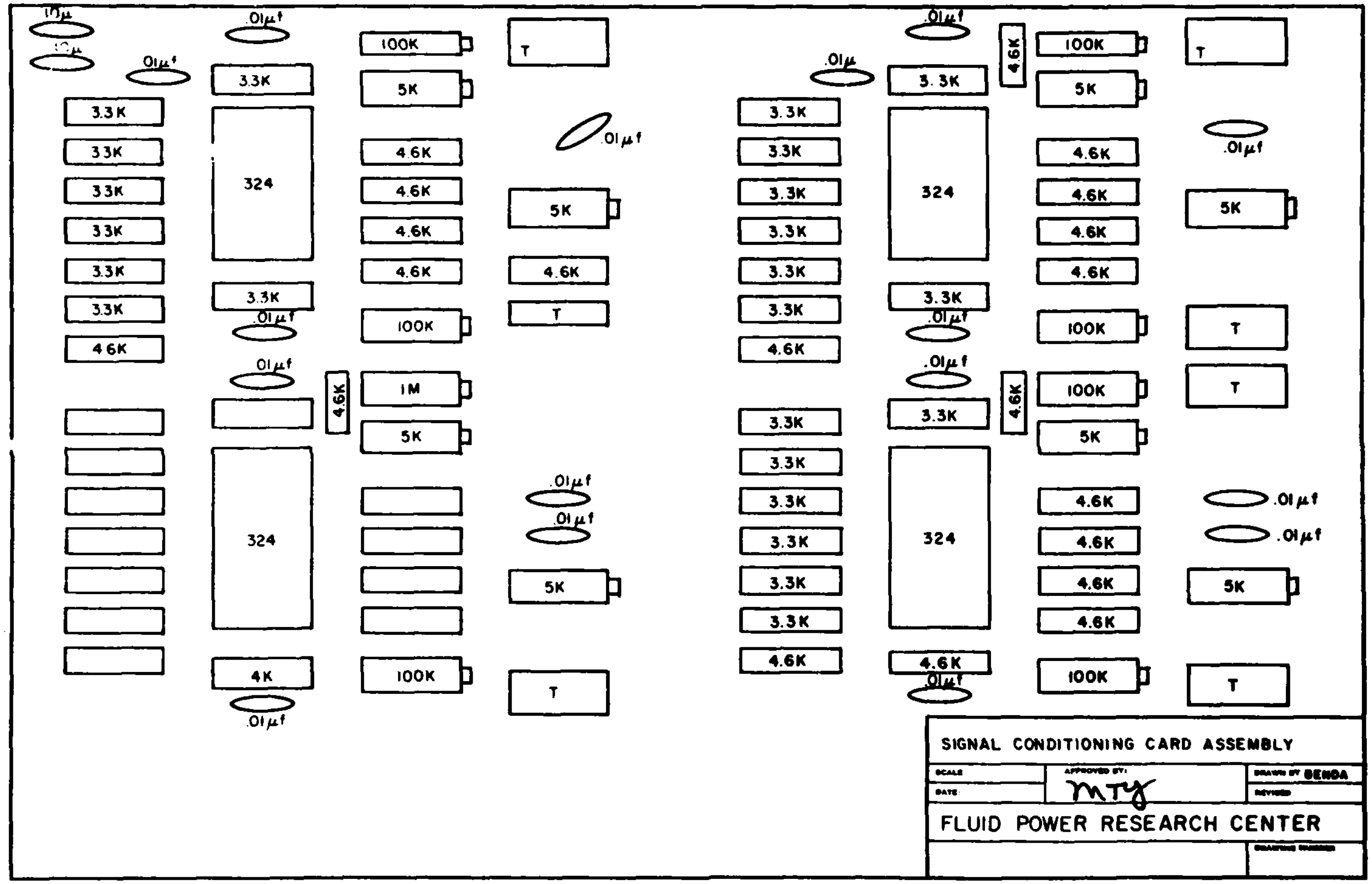


Fig. B-12 Signal Condition Card Assembly Drawing

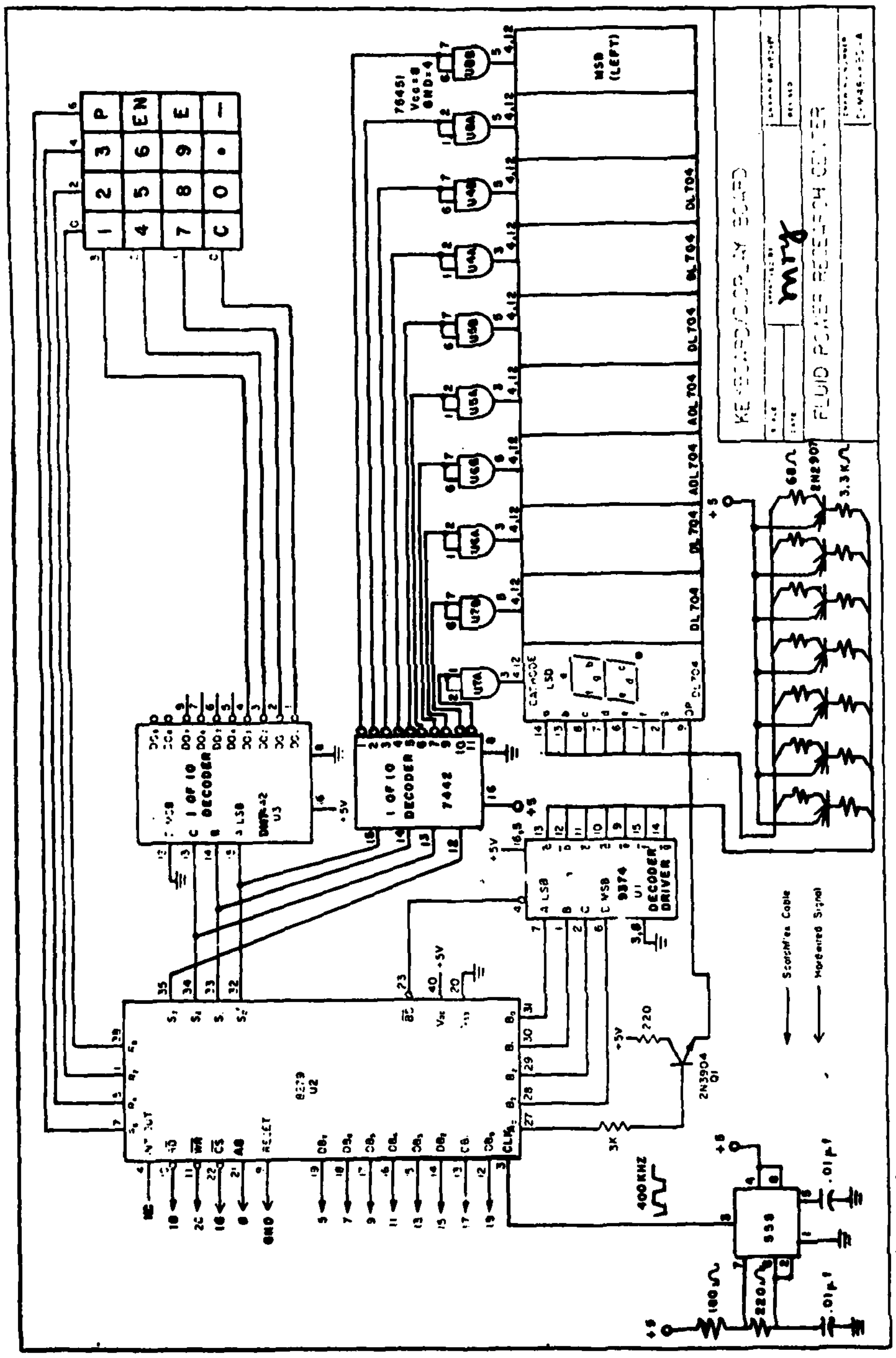


Fig. B-13 Keyboard/Display Board Schematic

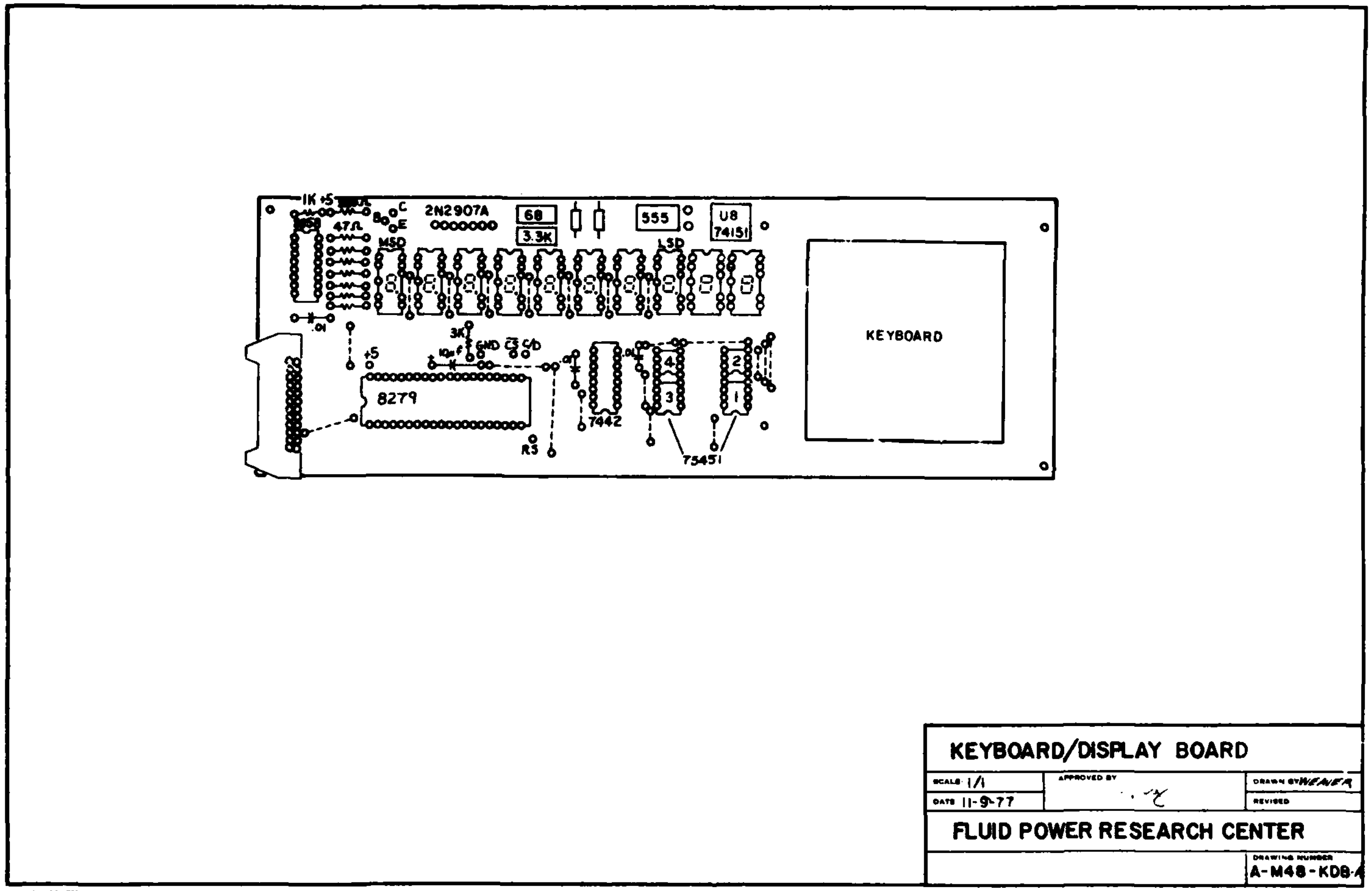
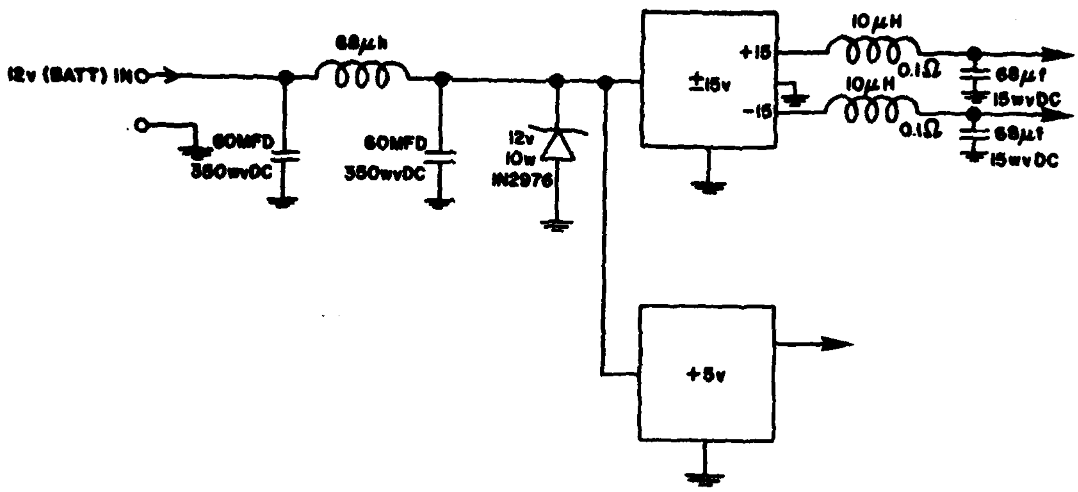
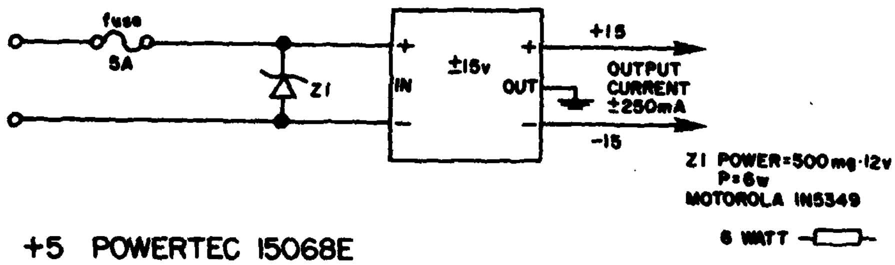


Fig. B-14 Keyboard/Display Board Assembly Drawing

POWER SUPPLY



SEMICONDUCTOR CIRCUITS, INC.
Model RD 12-15D250



+5 POWERTEC 15068E
5v REGULATOR

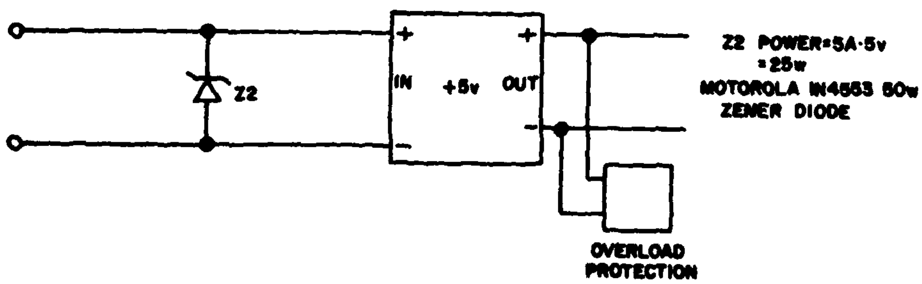


Fig. B-15 Power Supply Schematic

FRONT PANEL
SWITCHES & LED'S

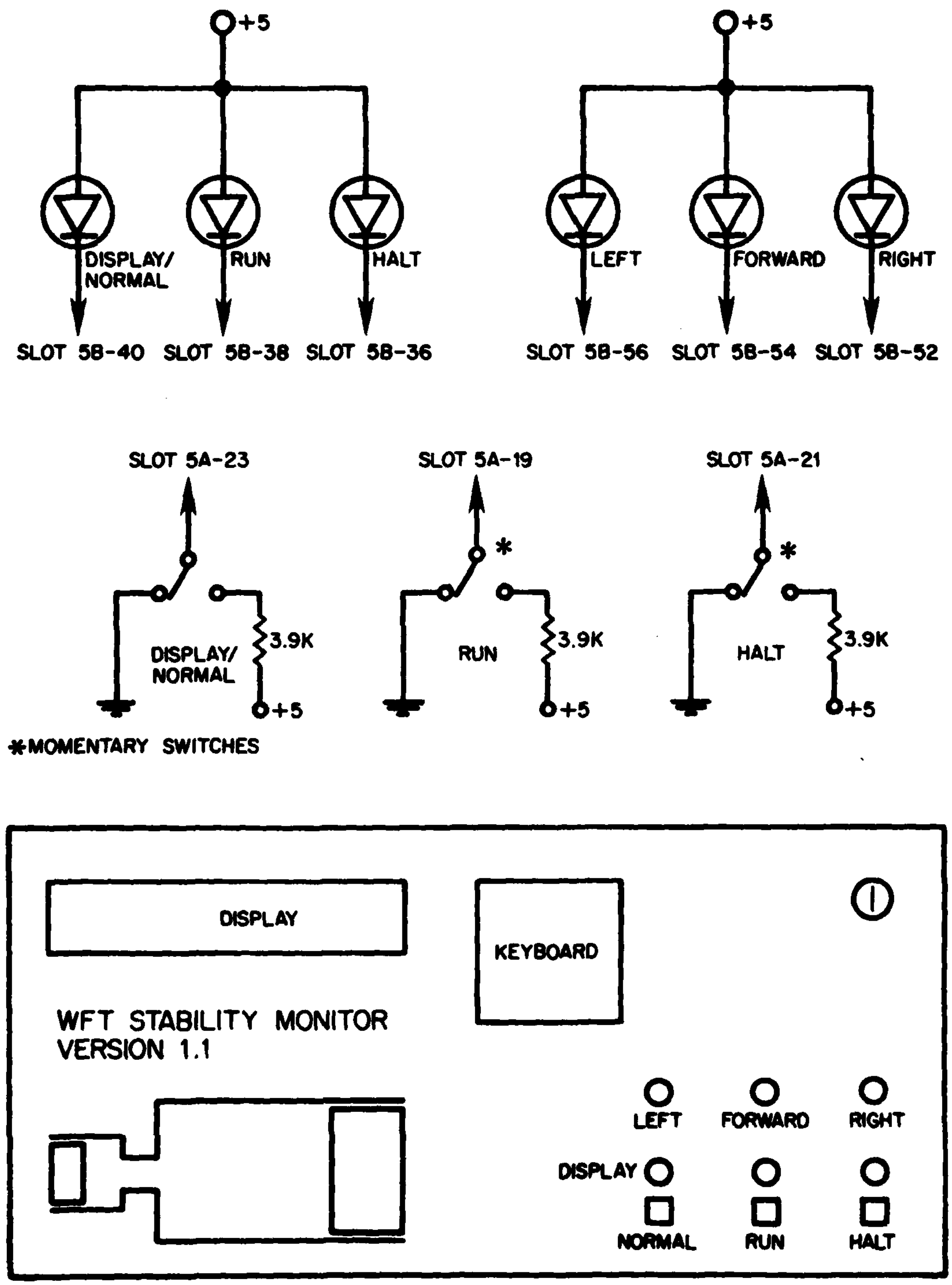
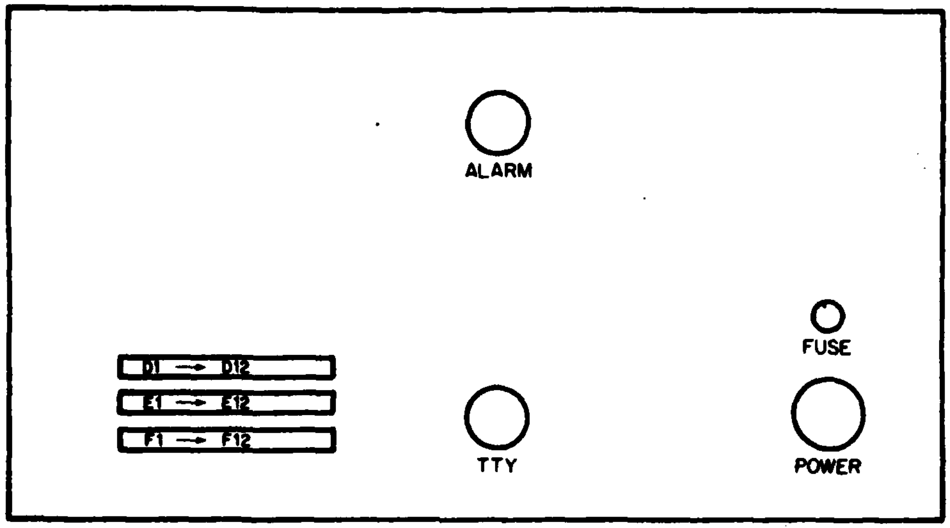
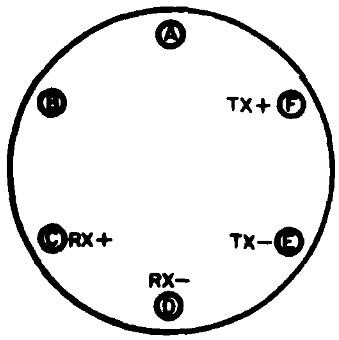


Fig. B-16 Front Panel Schematic

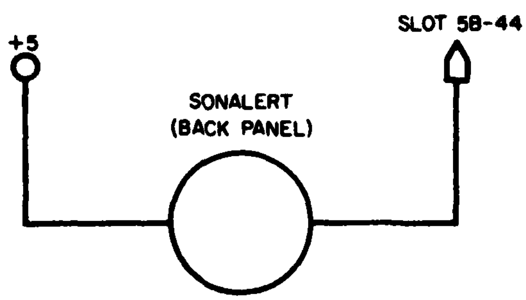
REAR PANEL



TTY CONNECTOR



PIN	FROM CARD	MOLEX
A	NC	5 RED
B	NC	6 BLK
C	SLOT 5B-17	3 WHT
D	SLOT 5B-25	4 GRN
E	SLOT 5B-33	2 BLK
F	SLOT 5B-35	1 RED

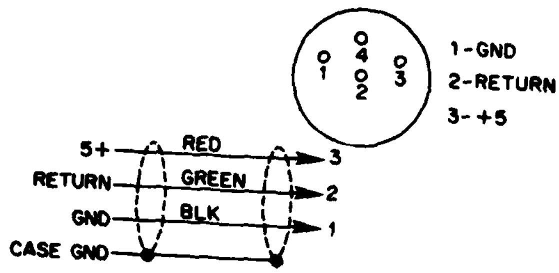


SONALERT MODEL SC628
6-28v DC
3-14 MA

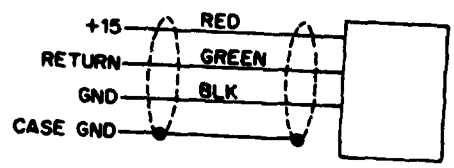
Fig. B-17 Rear Panel Schematic

XDUCERS

I. ANGLE XDUCERS HUMPHREY Model CP17-0601-1



II. PRESSURE XDUCERS NATIONAL



III. STRAIN XDUCER LEBROW

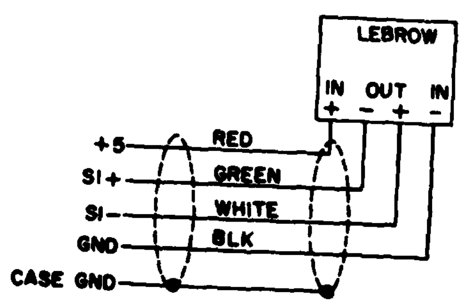
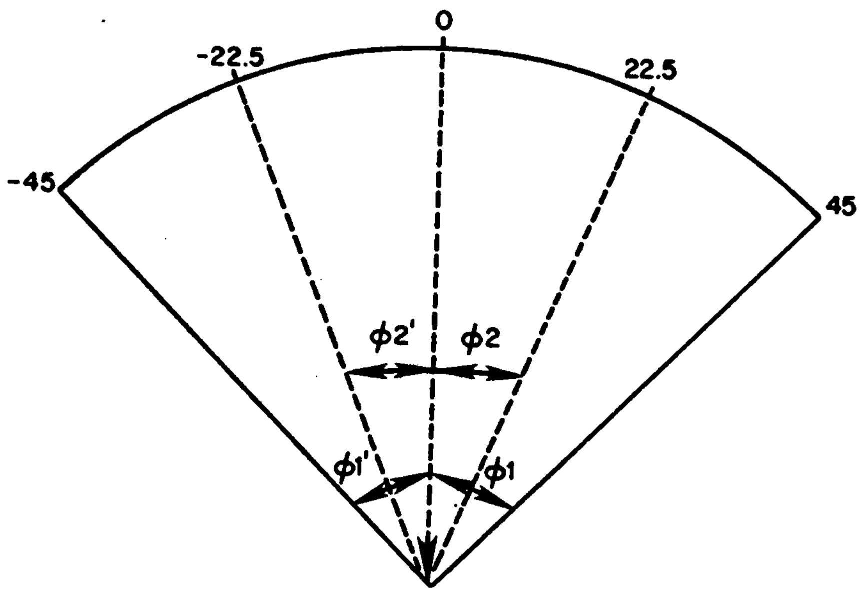


Fig. B-18 Transducer Connections

HUMPHREY ANGLE XDUCER



ANGLE	VOLTS
45	5v
22.5	3.75v
0	2.5v
-22.5	1.25v
-45	0

Fig. B-19 Angle Transducer Calibration

The following tables document the interconnection between the various computer cards. The tables detail a description of each signal line (interconnect line), its point of interconnecting (i.e., its source or destination) and its position on the edge connector (assignment). The following notation has been used:

Slot 7A-16	refers to edge connector position 16 on card 7 of card rack A.
ADϕ thru AD7	Micro computer data bus
A8 thru A15	Signals (refer to schematics).
WR,RD,ALE $10/\overline{M}$	
DO-A/D thru D11-A/D	Analog to digital converter data
Bus	Refers to microcomputer data bus. Interconnect accomplished by bused data lines on the Motherboard (Note: motherboard is the printed circuit board which interconnects the various cards in the card rack.).
Do-Nut	A plated-thru hole has been provided on the motherboard for connecting wires to the motherboard.
(H.W.)	Hardwired - A separete wire has been added.
NC	No connection

CARD RACK

SLOT ASSIGNMENTS

Slot	Card Name / Function	
1A	-----BLANK-----	RACK A
2A	-----RAM EXPANSION-----	
3A	RAM	
4A	CPU	
5A	PPI #1 (A/D CONTROL)	
6A	-----BLANK-----	
7A	A/D	
8A	SIGNAL CONDITIONING	
1B	-----BLANK-----	RACK B
2B	CMOS RAM	
3B	-----RAM EXPANSION-----	
4B	EPROM	
5B	PPI #2 (BUFFER, TTY, ALARM)	
6B	-----BLANK-----	
7B	-----BLANK-----	
8B	SIGNAL CONDITIONING (STRAIN)	

Table B-1 Card Rack Assignment

CARD RACK

SLOT ASSIGNMENTS

Slot	Card Name / Function	
1A	-----BLANK-----	
2A	-----RAM EXPANSION-----	
3A	RAM	
4A	CPU	RACK A
5A	PPI #1 (A/D CONTROL)	
6A	-----BLANK-----	
7A	A/D	
8A	SIGNAL CONDITIONING	
1B	-----BLANK-----	
2B	CMOS RAM	
3B	-----RAM EXPANSION-----	
4B	EPROM	RACK B
5B	PPI #2 (BUFFER, TTY, ALARM)	
6B	-----BLANK-----	
7B	-----BLANK-----	
8B	-----BLANK-----	

Table B-1 Card Rack Assignment

Table B-2 CMOS RAM Interconnect

CMOS RAM CARD
SLOT 2B Page 1 Of 2

Card Edge	From Card Edge	Description
1	+5	
2	+5	
3	GND	
4	GND	
5	+15V	
8	BUS	AD7
9	SLOT 5B-26	CMOS CONTROL
10	BUS	AD6
12	BUS	AD5
14	BUS	AD4
16	BUS	AD3
18	BUS	AD2
20	BUS	AD1
22	BUS	AD0
25	BUS	ALE
27	BUS	$\overline{WR}$
29	BUS	$\overline{RD}$
31	BUS	IO/$\overline{M}$
37	BUS	A8
39	BUS	A9
41	BUS	A10
43	BUS	A11
44 (H.W.)	SLOT 4A-38	POWER INTERRUPT

45	BUS	A12
47	BUS	A13
49	BUS	$\overline{A13}$
51	BUS	A14
53	BUS	$\overline{A14}$
55	BUS	A15

Table B-2 (Continued)

Table B-3 CPU & EPROM Interconnect

SLOT 4A - CPU Card &
SLOT 4B - EPROM Card
Page 1 of 2

Card Edge	From Card Edge	Description
1	+5	
2	+5	
3	GND	
4	GND	
8	BUS	AD7
10	BUS	AD6
12	BUS	AD5
14	BUS	AD4
16	BUS	AD3
18	BUS	AD2
20	BUS	AD1
22	BUS	AD0
24	DO-NUT	SO*
25	BUS	ALE
26	DO-NUT	$\overline{\text{INTA*}}$
27	BUS	$\overline{\text{WR*}}$
28	GND	INTER * (Grounded so no interrupt)
29	BUS	$\overline{\text{RD}}$
30	GND	RST 5.5* (Grounded so no interrupt)
31	BUS	IO/$\overline{\text{M}}$
32	GND	RST 6.5* (Grounded so no interrupt)
34	DO-NUT	SI*

SLOT 4A - CPU Card &
SLOT 4B - EPROM Card
Page 2 of 2

Card Edge	From Card Edge	Description
36 H.W.		RST 7.5*
37	BUS	A8
38	SLOT 2B	TRAP*
39	BUS	A9
40 H.W.	+5 Pullup (DO-NUT)	READY*
41	BUS	A10
42	DO-NUT	SID*
43	BUS	A11
44		$\overline{\text{RESET IN*}}$
45	BUS	A12
46	DO-NUT	SOD*
47	BUS	A13
48	NC	CLK*
49	BUS	A$\overline{13}$
50	BUS	RESET OUT*
51	BUS	A14
52	DO-NUT	HLDA*
53	BUS	A$\overline{14}$
54	GND	HOLD*
55	BUS	A15

* Not used on EPROM Board

Table B-3 (Continued)

Table B-4 I/O Card 00-03 Interconnect

SLOT 5A
#1 I/O Card 00-03
Page 1 of 2

Card Edge	From Card Edge	Description
1	+5	
2	+5	
3	GND	
4	GND	
7	Slot 7A-19	A2-A/D Channel Address
8	BUS	AD7
9	Slot 7A-17	A1-A/D Channel Address
10	BUS	AD6
11	Slot 7A-36	D1-A/D Data Out
12	BUS	AD5
13	Slot 7A-20	D2-A/D Data Out
14	BUS	AD4
15	Slot 7A-38	D3-A/D Data Out
16	BUS	AD3
17	Slot 7A-18	D4-A/D Data Out
18	BUS	AD2
19 (H.W.)	Front Panel (Run Switch)	Run Switch (Front Panel)
20	BUS	AD1
21(H.W.)	Front Panel (Halt Switch)	Halt Switch (Front Panel)
22	BUS	AD0
23(H.W.)	Front Panel (Display/Normal)	Display/Normal Switch

Table B-4 (continued)

SLOT 5A
#1 I/O Card 00-03
Page 2 of 2

Card Edge	From Card Edge	Description
24	Slot 7A-21	A3 A/D Channel Address
27	BUS	$\overline{WR}$
29	BUS	$\overline{RD}$
31	BUS	IO/$\overline{M}$
32	Slot 7A-34	A/D $\overline{STROBE}$
34	Slot 7A-23	A4 A/D Channel Address
36	Slot 7A-40	D5-A/D Data Out
37	BUS	A8
38	Slot 7A-16	D6-A/D Data Out
39	BUS	A9
40	Slot 7A-52	D7-A/D Data Out
41	BUS	A10
42	Slot 7A-14	D8-A/D Data Out
43	BUS	A11
45	BUS	A12
47	BUS	A13
48	Slot 7A-54	D9-A/D Data Out
49	BUS	A$\overline{13}$
50	BUS	RESET OUT
51	BUS	A14
52	Slot 7A-15	D10-A/D Data Out
53	BUS	A14
54	Slot 7A-56	D11-A/D Data Out
56	Slot 7A-13	D12 (LSB) A/D Data Out

Table B-5 I/O Card ϕ 8 Interconnect

SLOT 5B
I/O Card 08-0B
Page 1 of 2

Card Edge	From Card Edge	Description
1	+5	
2	+5	
3	GND	
4	GND	
5	-15	
8, 10	BUS	AD7, AD6
12	BUS	AD5
14	BUS	AD4
16	BUS	AD3
17 (H.W.)	6P-C	TTY INPUT
18	BUS	AD2
20	BUS	AD1
22	BUS	ADϕ
25	6P-D	RX-
26 (H.W.)	SLOT 2B-9	CMOS CONTROL
27	BUS	$\overline{WR}$
29	BUS	$\overline{RD}$
31	BUS	IO/$\overline{M}$
35 (H.W.)	6P-F	TTY OUTPUT
36	FRONT PANEL (HALT)	HALT LED
37	BUS	
38	FRONT PANEL (RUN)	AB RUN LED

SLOT 5B
I/O Card 08-0B
Page 2 of 2

Card Edge	From Card Edge	Description
39	BUS	
40	FRONT PANEL (DISPLAY/NORMAL)	A9 DISPLAY/NORMAL LED
41	BUS	A10
43	BUS	A11
44	BACK PANEL (ALARM)	ALARM
45	BUS	A12
47	BUS	A13
49	BUS	$\overline{A13}$
50	BUS	RESET OUT
51	BUS	A14
52 (H.W.)	FRONT PANEL (RIGHT LED)	RIGHT LED
53	BUS	$\overline{A14}$
54 (H.W.)	FRONT PANEL (FORWARD LED)	FORWARD LED
56 (H.W.)	FRONT PANEL (LEFT LED)	LEFT LED

Note: (H.W.) denotes hard-wired, line, nonexistent on Mother Board.

Table B-5 (Continued)

Table B-6 A/D Converter Interconnect

SLOT 7A
A/D Converter
Page 1 of 2

Card Edge	From Card Edge	Description
1, 2	+5V	
3, 4	Digital GND	
8	+15	
10	-15	
11	ANALOG GND	
13	Slot 5A-56	A/D Data 12
14	Slot 5A-42	A/D Data 8
15	Slot 5A-52	A/D Data 10
16	Slot 5A-38	A/D Data 6
17	Slot 5A-9	A/D Channel Address A1
18	Slot 5A-17	A/D Data 4
19	Slot 5A-7	A/D Channel Address A2
20	Slot 5A-13	A/D Data 2
21	Slot 5A-24	A/D Channel Address A3
23	Slot 5A-34	A/D Channel Address A4
25, 27, 29 31, 33	Slot 7A-11	ANALOG GND to unused A/D inputs
34	Slot 5A-32	A/D STROBE
35	Slot 7A-11	ANALOG GND to unused A/D inputs
36	Slot 5A-11	A/D Data 1
37		
38	Slot 5A-15	A/D Data 3
39	F-12	Limit Switch 2 (Reverse)
40	Slot 5A-36	A/D Data 5

		SLOT 7A A/D Converter Page 2 of 2
41	Slot 8A-12	P1
43	Slot 8A-16	P2
45	Slot 8A-20	P3
47	Slot 8A-26	A1 Angle
49	Slot 8A-32	A2 Angle
51	Slot 8A-38	A3 Angle
52	Slot 5A-40	A/D Data 7
53	Slot 8A-44	S1 Strain
54	Slot 5A-48	A/D Data 9
55	F-11	Limit Switch 1 (fwd.)
56	Slot 5A-54	A/D Data 11

Table B-6 (Continued)

Table B-7 Signal Conditioning Interconnect

SLOT 8A
SIGNAL CONDITIONING
Page 1 of 3

Card Edge	From Card Edge	Description
1	+5	
2	+5	
3	GND	
4	GND	
5	+15	
6	+15	
7	-15	
8	-15	
9	ANALOG GND	
10	ANALOG GND	
11	D1	P1(+) -IN
12	SLOT 7A-41	P1 - OUT
13	D2	P1(-) -IN
14	NC	NC
15	D5	P2(+) -IN
16	SLOT 7A-43	P2 - OUT
17	D6	P2(-) -IN
18	NC	NC
19	NC	NC
20	SLOT 7A-45	P3 - OUT
21	D9	P3(+) - IN
22	NC	NC
23	D10	P3(-) -IN
24	NC	NC

Table B-7a (continued)

Slot 8A
SIGNAL CONDITIONING
Page 2 of 3

Card Edge	From Card Edge	Description
25	NC	NC
26	SLOT 7A-47	A1 - OUT
27	E3	A1(+) - IN
28	NC	NC
29	E2	A1(-) -IN
30	NC	NC
31	NC	NC
32	SLOT 7A-49	A2 - OUT
33	E7	A2(+) -IN
34	NC	NC
35	E6	A2(-) -IN
36	NC	NC
37	NC	NC
38	SLOT 7A-51	A3 - OUT
39	E11	A3(+) -IN
40	NC	NC
41	E10	A3(-) -IN
42	NC	NC
43	NC	NC
44	NC	NC
45	NC	NC

Table B-7a (continued)

Slot 8a
SIGNAL CONDITIONING
Page 3 of 3

Card Edge	From Card Edge	Description
46	NC	NC
47	NC	NC
48	NC	NC
49	NC	NC
50	NC	NC
51	NC	NC
52	NC	NC
53	NC	NC
54	NC	NC
55	NC	NC
56	NC	NC

DX
EX Terminal strips
FX

Table B-7 Signal Conditioning Interconnect

SLOT 8A
SIGNAL CONDITIONING
Page 1 of 3

Card Edge	From Card Edge	Description
1	+5	
2	+5	
3	GND	
4	GND	
5	+15	
6	+15	
7	-15	
8	-15	
9	ANALOG GND	
10	ANALOG GND	
11	D1	P1(+) -IN
12	SLOT 7A-41	P1 - OUT
13	D2	P1(-) -IN
14	NC	NC
15	D5	P2(+) -IN
16	SLOT 7A-43	P2 - OUT
17	D6	P2(-) -IN
18	NC	NC
19	NC	NC
20	SLOT 7A-45	P3 - OUT
21	D9	P3(+) - IN
22	NC	NC
23	D10	P3(-) -IN
24	NC	NC

Table B-7 (continued)

SLOT 8A
SIGNAL CONDITIONING
Page 2 of 3

Card Edge	From Card Edge	Description
25	NC	NC
26	SLOT 7A-47	A1 - OUT
27	E3	A1(+) -IN
28	NC	NC
29	E2	A1(-) -IN
30	NC	NC
31	NC	NC
32	SLOT 7A-49	A2 - OUT
33	E7	A2(+) -IN
34	NC	NC
35	E6	A2(-) -IN
36	NC	NC
37	NC	NC
38	SLOT 7A-51	A3 - OUT
39	E11	A3(+) -IN
40	NC	NC
41	E10	A3(-) -IN
42	NC	NC
43	NC	NC
44	SLOT 7A-53	S1 - OUT
45	F3	S1(+) -IN
46	NC	NC
47	F4	S1(-) -IN
48	NC	S2 - OUT

Table B-7 (Continued)

SLOT 8A
SIGNAL CONDITIONING
Page 3 of 3

Card Edge	From Card Edge	Description
49	NC	S2(+) -IN
50	NC	NC
51	NC	S2(-) -IN
52	NC	NC
53	NC	NC
54	NC	NC
55	NC	NC
56	NC	NC

DX, EX, FX: Terminal Strips

Table B-7b Signal Conditioning Interconnect (Strain)

SLOT B
SIGNAL CONDITIONING (STRAIN)
Page 1 of 1

Card Edge	From Card Edge	Description
8	F4 Rear Panel	S_1(-) Input
10	F3 Rear Panel	S_1(+) Input
12		S_1 Output
46	-15VDC	
50	Analog Gnd	
54	+15VDC	

Table B-8 Port Assignments

Port Assignments

PPI #1

ADDRESS
00-03
SLOT 5A

Port Address	8255 Port	Pin	Description				
00	A0	56	A/D	DATA	12 LSB		INPUT
	A1	54	"	"	11		"
	A2	52	"	"	10		"
	A3	48	"	"	9		"
	A4	42	"	"	8		"
	A5	40	"	"	7		"
	A6	38	"	"	6		"
	A7	36	A/D	DATA	5		INPUT
01	B0	9	A/D	CHANNEL	ADDRESS	A1	OUTPUT
	B1	7	"	"	"	A2	"
	B2	24	"	"	"	A4	"
	B3	34	A/D	CHANNEL	ADDRESS	A8	OUTPUT
	B4	32	A/D	STROBE			OUTPUT
	B5	30					
	B6	28					
	B7	26					
02	C0	17	A/D	DATA	4		INPUT
	C1	15	"	"	3		"
	C2	13	"	"	2		"
	C3	11	A/D	DATA	1 MSB		INPUT

C4	19	RUN SWITCH - INPUT
C5	21	HALT-SWITCH - INPUT
C6	23	DISPLAY/NORMAL - INPUT
C7	35	

03 CONTROL WORD

Table B-8 (Continued)

Table B-8 (continued)

PPI #2

ADDRESS
08-0B
SLOT 5B

PORT ADDRESS	8255 PORT	PIN	DESCRIPTION
08	AD	56	LEFT - OUT
	A1	54	PITCH - OUT
	A2	52	RIGHT - OUT
	A3	48	
	A4	42	
	A5	40	DISPLAY/NORMAL - OUT
	A6	38	RUN - OUT
	A7	36	HALT - OUT
09	B0	9	
	B1	7	
	B2	24	
	B3	34	
	B4	32	
	B5	30	
	B6	28	
	B7	26	CMOS CONTROL - OUT
0A	C0	17	TTY RECEIVER - INPUT
	C1	15	TTY/PKD - INPUT
	C2	13	
	C3	11	

	C4	19	
	C5	21	
	C6	23	
	C7	35	TTY SEND TO TTY - OUTPUT
OB	CONTROL WORD		

Table B-8 (Continued)

PKD SCOTCHFLEX CONNECTOR

Function	8279 Pin	Scotchflex Pin#		8279 Function
Reset	9	1	2	NC ----
555 Out	3	0	0	NC ----
AD7	19	0	0	NC ----
AD6	18	0	0	21 AB (C/D)
AD5	17	0	0	20 GND
AD4	16	0	0	NC ----
AD3	15	0	0	NC ----
AD2	14	0	0	22 $\overline{CS}$
AD1	13	0	0	10 $\overline{RD}$
AD0	12	019	200	11 $\overline{WR}$
		0	0	Clip off last three rows
		0	0	
		0	0	

Edge Connector

Table B-9 Display Connector Signal Assignments

MCS85 SCOTCHFLEX

Function	Scotchflex Pin#		Function
Reset	1	2	A11
ALE	3	4	A10
AD7	5	6	A9
AD6	7	8	A8
AD5	9	10	GND
AD4	11	12	IO/$\overline{M}$
AD3	13	14	+5
AD2	15	16	$\overline{CS}$ 8279 * on FPI #2 Only
AD1	17	18	$\overline{RD}$
AD0	19	20	$\overline{WR}$
A15	21	22	$\overline{A13}$
A14	23	24	$\overline{A14}$
A13	25	26	A12

Table B-10 MC585 Flex-Cable Assignment

APPENDIX C

VECTOR IDENTITIES

APPENDIX C

VECTOR IDENTITIES

1. Partial Derivative of a Cross Product

If (C-1)

$$\frac{\partial \bar{B}}{\partial \bar{A}_j} = 0$$

Then (C-2)

$$\frac{\partial (\bar{A} \times \bar{B})}{\partial \bar{A}_j} = \bar{B}^j$$

and (C-3)

$$\frac{\partial (\bar{B} \times \bar{A})}{\partial \bar{A}_j} = -\bar{B}^j$$

where (C-4)

$$\bar{B} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \quad \bar{B}^1 = \begin{bmatrix} 0 \\ -b_3 \\ b_2 \end{bmatrix} \quad \bar{B}^2 = \begin{bmatrix} b_3 \\ 0 \\ b_1 \end{bmatrix} \quad \bar{B}^3 = \begin{bmatrix} -b_2 \\ b_1 \\ 0 \end{bmatrix}$$

2. Triple Scalar Product

$$(\bar{P} \times \bar{Q}) \cdot \bar{R} = \bar{R} \cdot (\bar{P} \times \bar{Q}) = -\bar{R} \cdot (\bar{Q} \times \bar{P}) \tag{C-5}$$

also

$$P \times Q \cdot R = P \cdot Q \times R \tag{C-6}$$

APPENDIX D

INSTALLATION AND OPERATION

APPENDIX D

INSTALLATION AND OPERATION

The WFT Stability Monitor was designed to be installed on conventional counterbalanced warehouse lift trucks with an articulated rear axle. The system has no provisions for attachments, such as, side shift. Also, lift cylinders which power down are not considered.

The system is installed on the vehicle by first installing the transducers and then connecting the transducers to the Stability Monitor, which is then connected to a power source. System calibration adjustments must then be performed.

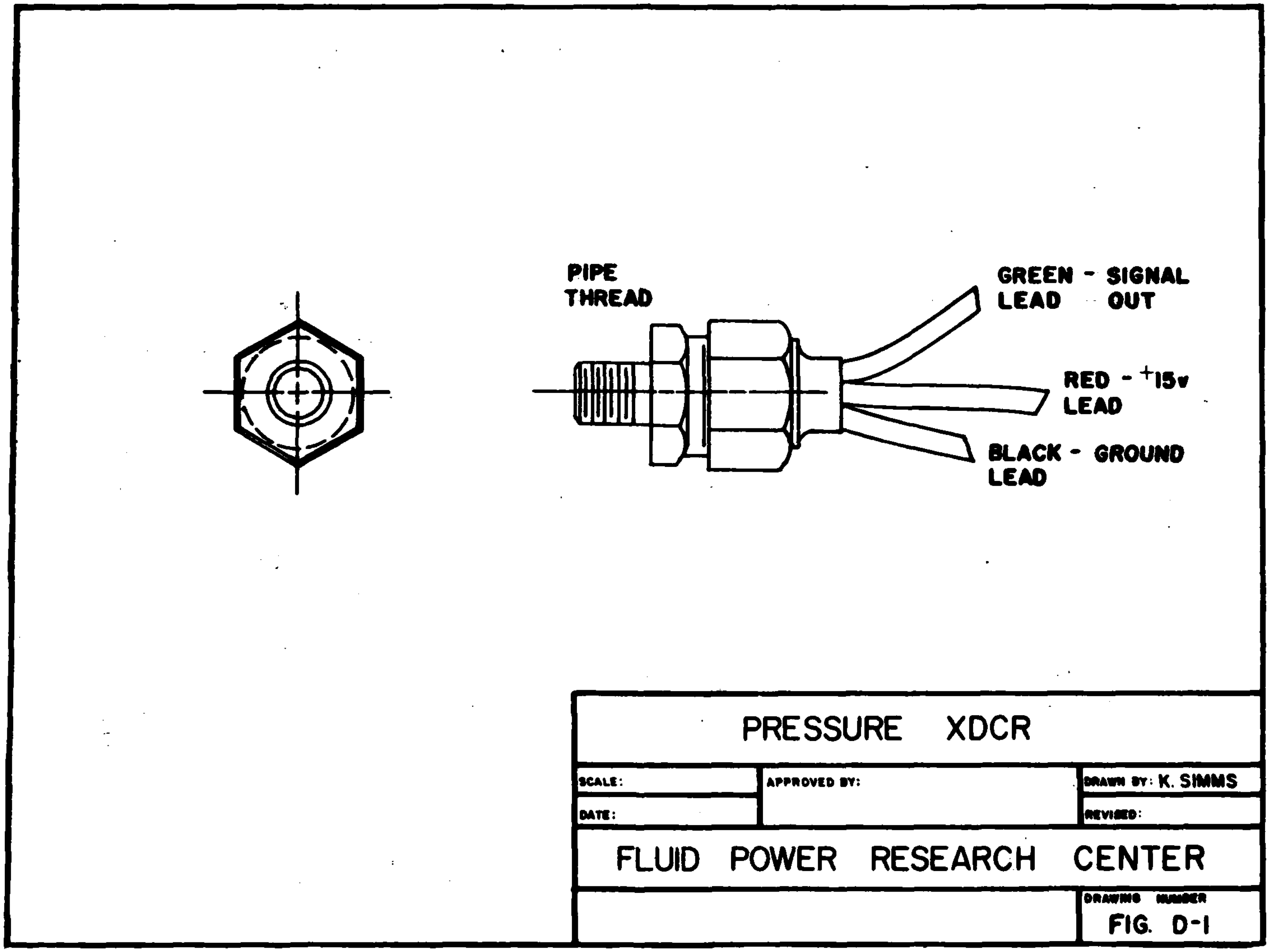
Installation

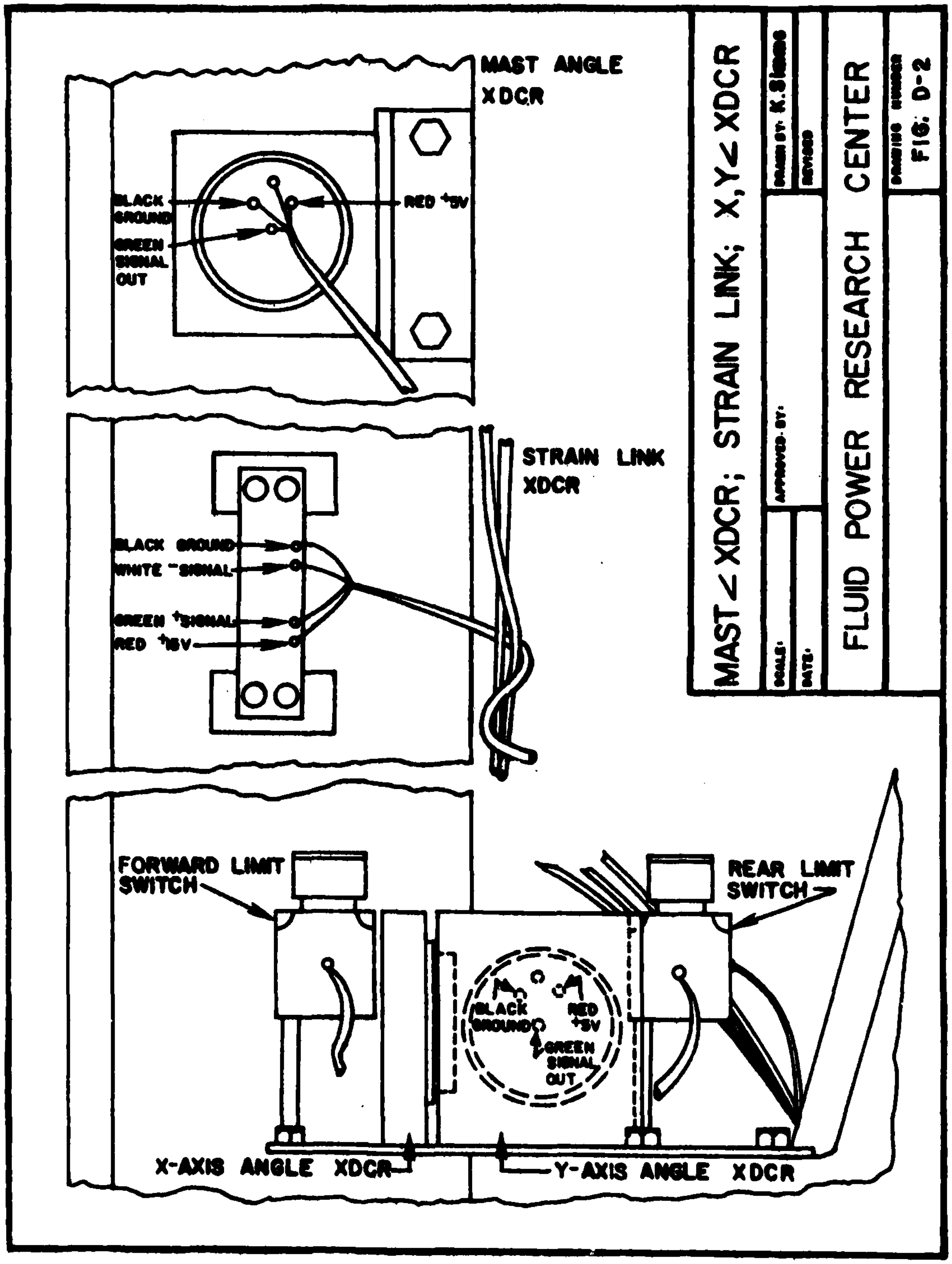
The following transducers must be installed:

1. Tilt Cylinder Rod-Side Pressure (P_1)*
2. Tilt Cylinder Head-Side Pressure (P_2)
3. Lift Cylinder Pressure (P_3)
4. Vehicle X-axis Angle (P_4)
5. Vehicle Y-axis Angle (P_5)
6. Mast Angle (P_6)
7. Side Load Strain (P_7)

The pressure transducers should be installed into the appropriate lines. (Refer to Fig D-1 for transducer connections.) The vehicle angle transducers (P_4 and P_5) are installed perpendicular to each other, P_4 along the X-axis (drive axle), and P_5 along the Y-axis in

*(P denotes parameter no.)


PIPE
THREAD
GREEN - SIGNAL
LEAD OUT
RED - +15v
LEAD
BLACK - GROUND
LEAD
PRESSURE XDCR
SCALE:
DATE:
APPROVED BY:
DRAWN BY: K. SIMMS
REVISED:
FLUID POWER RESEARCH CENTER
DRAWING NUMBER
FIG. D-1

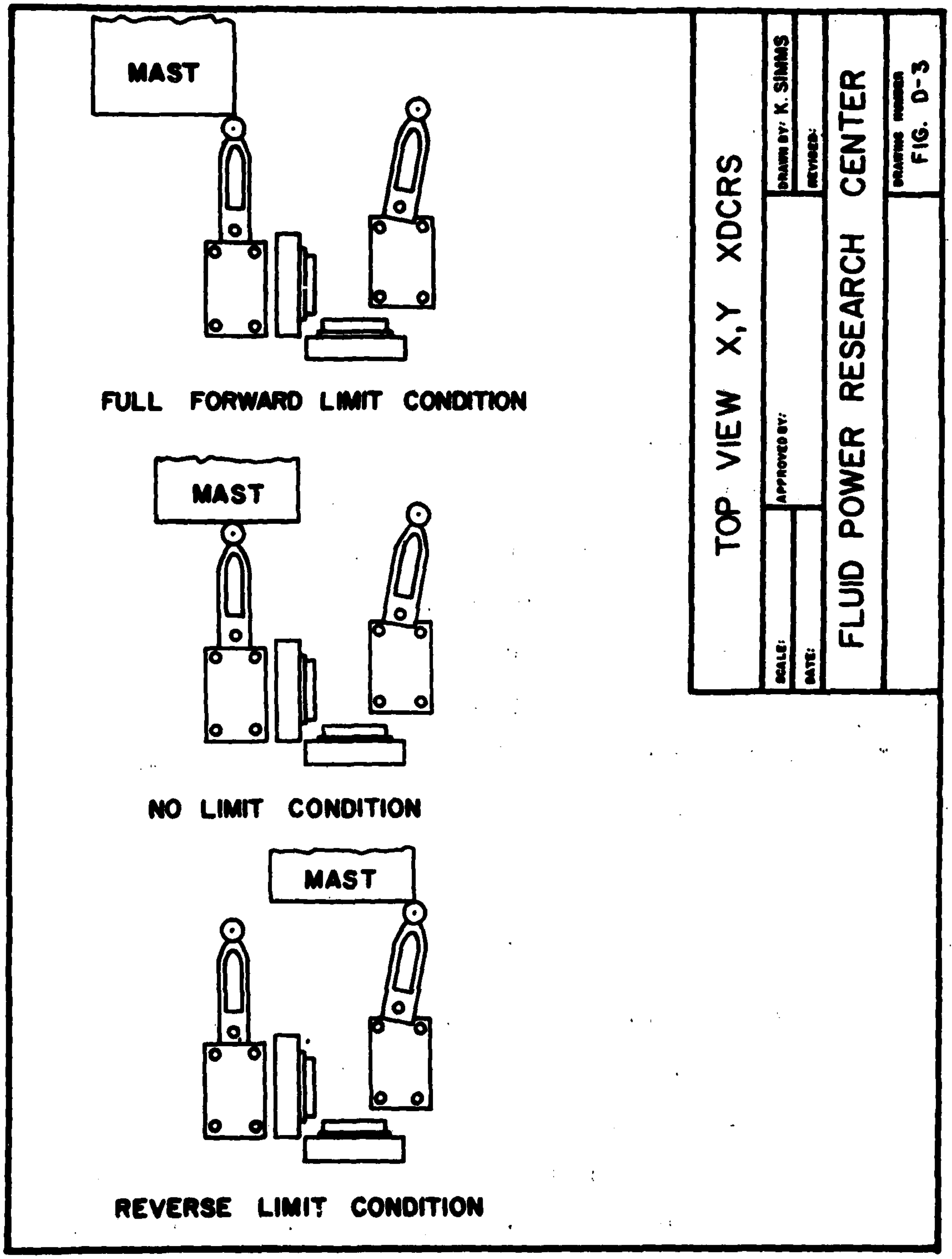

MAST ANGLE XDCR
BLACK GROUND
GREEN SIGNAL OUT
RED +5V
STRAIN LINK XDCR
BLACK GROUND
WHITE −SIGNAL
GREEN +SIGNAL
RED +15V
FORWARD LIMIT SWITCH
REAR LIMIT SWITCH
BLACK GROUND
RED +5V
GREEN SIGNAL OUT
X-AXIS ANGLE XDCR
Y-AXIS ANGLE XDCR
MAST∠XDCR; STRAIN LINK; X,Y∠XDCR
DRAWN BY: K.Simms
REVISED
SCALE:
DATE:
APPROVED BY:
FLUID POWER RESEARCH CENTER
DRAWING NUMBER
FIG: D-2

AD-A088 551 OKLAHOMA STATE UNIV STILLWATER FLUID POWER RESEARCH --ETC F/6 13/3
SECOND GENERATION LOAD STABILITY SENSOR DEVICE.(U)
MAY 80 E C FITCH, R L DECKER, M T YOKLEY DAAK70-78-C-0067

UNCLASSIFIED NL

3 of 3

END
DATE FILMED
10-80
DTIC


MAST
FULL FORWARD LIMIT CONDITION
MAST
NO LIMIT CONDITION
MAST
REVERSE LIMIT CONDITION
TOP VIEW X,Y XDCRS
DRAWN BY: K. SIMMS
REVISED:
APPROVED BY:
SCALE:
DATE:
FLUID POWER RESEARCH CENTER
DRAWING NUMBER
FIG. D-3

a manner such that zero degrees is indicated when the vehicle is on a level surface. This allows vehicle orientation to be determined. (Figures D-2, D-3)

The mast angle transducer should be installed on the mast, as shown in figure D-2. This will typically require welding a bracket onto the mast to allow for mounting the angle transducer assembly.

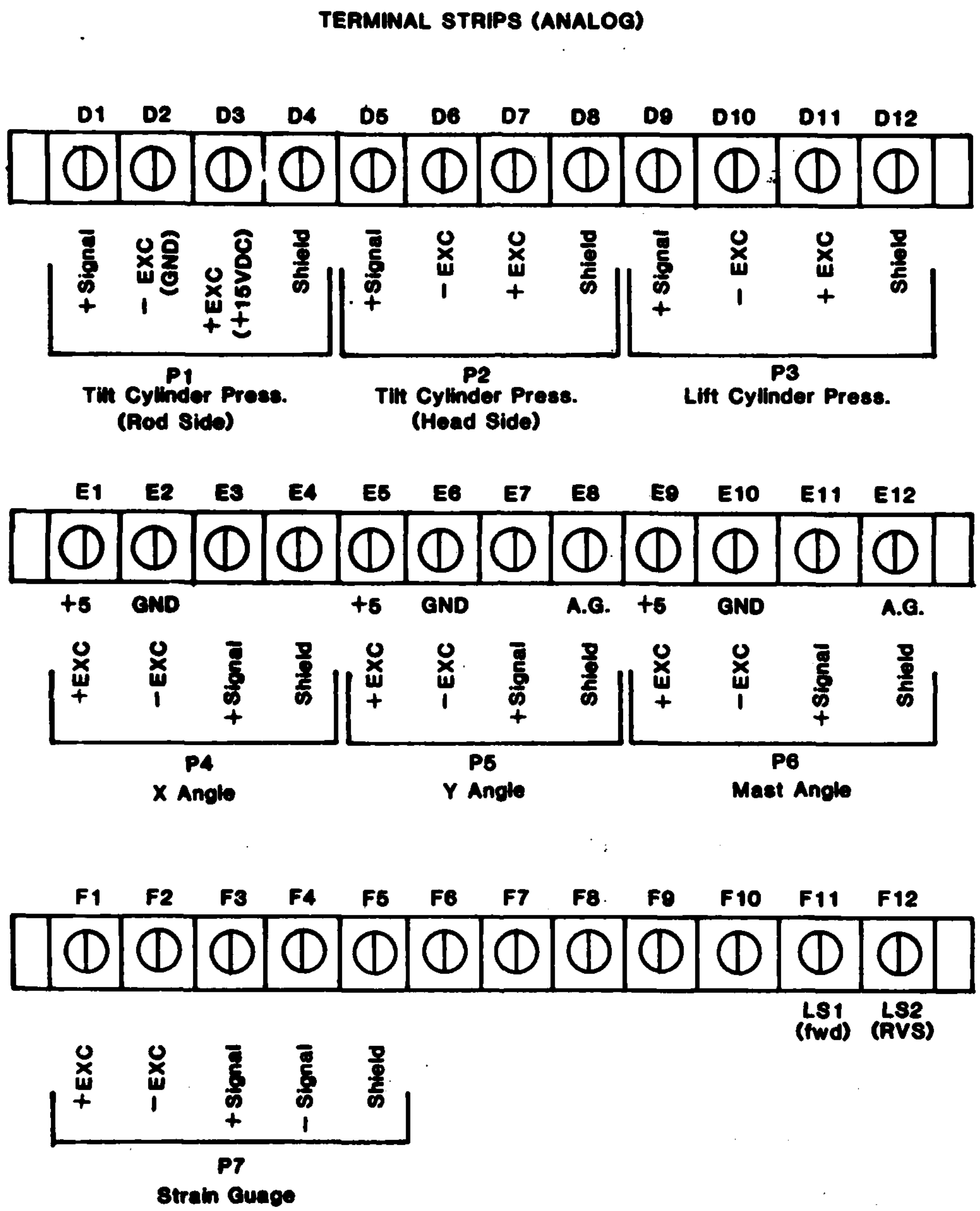
The side load strain is measured via the four-arm Strain-Link attached to the driver's left side of the mast assembly. With the mast vertical, the link is installed on the outermost portion of the stationary part of the mast, oriented vertically. Figure D-2 shows the location of the gauge on the side of the mast. The Strain-Link eliminates the need for gauges mounted on both mast uprights. Connect all 7 transducers to the back panel as indicated in Figure D-4.

Before assembling the WFT Stability Monitor, visually inspect for loose wiring, etc. inside the enclosure. Remove all P. C. cards. The System should be connected to a 12 VDC ± 2VDC power source capable of supplying 4 amps. This connection is as follows:

+ 12 VDC	J1-A (Black/White)
Ground	J1-C (Red/Green)

Connect the power plug and rotate the key-lock on the front-panel to apply power to the system. Check the outputs of the two power-supplies to insure 1% tolerance on the specified values (See Appendix E).

Turn power off and insert the circuit cards into their respective card-rack locations. These are shown on the lid decal, and listed in



Note: +EXC, -EXC are +Excitation and -Excitation, resp.

Figure D-4

Transducer Connections to Back Panel

Appendix B. Apply power to the system and observe the display blanking. The HALT Switch lamp should be lighted. To test the unit operation depress the following keys (order from left to right):

P 8 En

The value of Parameter eight (P8) should be displayed. The correct value for this geometric parameter should be entered into the Monitor from table 4-1 (geometric parameter values). This data entry is accomplished by depressing the proper numeric keys, followed by the En key (Enter). Then display the stored value of P8 and compare to the value just entered. This sequence, successfully completed, insures proper electronic operation of the Monitor. However, transducer signals and calibration must be correct for proper Monitor operation.

Operation

The operation of the Stability Monitor is quite simple due to the small number of controls and operator inputs required. Fundamental operation is discussed here.

a.) Power is applied with key-switch rotated to position ON.

b.) Select NORMAL or DISPLAY mode with alternate action front panel switch - this selects whether an update will be made to a displayed parameter during Monitor program execution. If DISPLAY mode is selected, the last parameter keyed-in will be constantly updated. When NORMAL mode is selected (switch is lit), no parameter is displayed. This prevents any speed degradation when operating in a critical environment.

† 'Denotes constant'

Program Assignment	Equation Variable	Program Assignment	Equation Variable
P1	Pressure rod side	P25	A_{Lift} †
P2	Pressure head side	P26	Y_T †
P3	Pressure lift	P27	k (for σ) †
P4	(Angle 1) θx meas, θx calc.	P28	W_{mast} †
P5	(Angle 2) θy meas, θy calc.	P29	$PR2_x$ †
P6	(Angle 3) $\theta_{m_{meas}}$	P39	$\cos \theta_T$
P7	σ (Strain)	P40	$\sin \sigma_T$
P8	X_v †	P41	λ_{RRX}†
P9	W_v †	P42	λ_{RRY}†
P10	Y_v †	P43	λ_{RRZ}†
P11	Z_v †	P44	$S_{pitch\ Limit}$ †
P12	X_vW_v †	P45	$S_{LR\ Limit}$ †
P13	Y_vW_v †	P46	$S_{RR\ Limit}$ †
P14	Z_vW_v †		
P15	Z_m-Z_T †		
P16	Z_m †		
P17	Z_T †		
P19	X_m †		
P20	λ_{LRX} †		
P21	λ_{LRY} †		
P22	λ_{LRZ} †		
P23	$A_{head\ side}$†		
P24	$A_{rod\ side}$ †		

Table D-1

Program Parameter Definitions

c.) The keyboard (when in HALT mode) will allow parameter entry and examination. All system geometric parameters must be entered before first-time operation. They are stored in memory, having battery power for data retention of approximately 3 weeks should the key switch or power plug be turned off or removed. This prevents the necessity of entering them each time power is turned off.

When it is desired to examine a parameter, the following key sequence is used:

$\boxed{P}$ $\boxed{n}$ $\boxed{En}$ The value of parameter "n" ("n" = 1 to 46) is then displayed in scientific notation.

To <u>change</u> a parameter value, use this sequence:

$$\boxed{P}\ \boxed{n}\ =\ \boxed{m_1}\ \boxed{m_2}\ \boxed{m_3}\ \boxed{m_m}\ \boxed{En}$$

Where "n" is the parameter number and $m_1 .. m_m$ are the numeric keys constituting the desired value. The value may be entered in scientific notation or as an integer, but internally is converted to floating-point notation.

A clear key $\boxed{C}$ is available to "erase" key closures. The $\boxed{E}$ key is an exponent designator. A minus $\boxed{-}$ key is included for negative values and the $\boxed{En}$ key represents the "Enter" function. All keys are displayed as they are depressed.

d.) The RUN switch is used to begin Monitor program execution. The HALT switch allows program termination. Both commands have lamps to indicate when active.

e.) Should an unstable configuration occur, the respective axis

L.E.D. indicator will light and the audio alarm will sound.

APPENDIX E

CALIBRATION PROCEDURES

APPENDIX E

CALIBRATION PROCEDURES

The calibration of various system components must be maintained to ensure a properly functioning system. Specific procedures relating to each assembly follow.

Power Supplies

Both system D.C. power supplies located on the rear panel must be maintained at their nominal value to enable the Monitor to operate. Excessive power supply voltages could destroy some electronic components and low voltage can cause faulty operation. The adjustments of the supplies should be done with a calibrated voltmeter to the following specification, with +5v checked at the CPU (test point provided) and ±15v at the signal conditioning card, and all cards inserted:

5v regulator: +5 D.C. ±1%

±15v converter: +15 D.C. ±1%

The +5V overvoltage protection circuit should be adjusted to an approximate value of 6.2 volts. The actual potentiometers are located on the respective circuits bolted to the rear panel.

Transducers

The calibration of the system transducers is very critical to performance.

a) <u>Input Signal Error</u>

All analog inputs must be calibrated for a 0-5V D.C. range out

of the appropriate channel on the signal conditioning card. The following list in Table E-1 shows all the inputs and their analog ranges.

Any deviation from the full scale voltage of +5.0V will cause an error in analog units equivalent to:

$$\text{Error} = \frac{A * V}{5}$$

where: A is the full scale analog value

V is the error voltage (<u>from</u> +5.0V D.C.)

e.g. for P1; A = 3000 psi, let V = 0.95; Error = $\frac{3000\ (0.95)}{5}$ = 570 psi error at full scale.

Therefore, noise voltage, or calibration error on the analog signal, can be significant.

<u>FP/1 Calibration Equations</u>

The μC stores two values in the calibration table for each analog parameter measured. These values are used to scale the A/D output reading to obtain proper engineering units. (i.e. psi, degrees, etc.) from the transducer signal. Therefore, a calibration equation is executed each time an analog parameter is measured. This equation is of the form:

Parameter value = A * (A/D output) + B

where:

A = Gain

B = Offset

The derivation of the present calibration table (CALBR) values are shown below. This calibration information is used by the FP/1 MEAS

η, /

MEASURED INPUTS

TABLE E-1

Parameter	Range	Transducer Output	FP/1 Design-ator	A/D Channel
Pressure-Tilt cylinder rod side	0-3000 p.s.i.	2.51v-12.51v	P1	0
Pressure-Tilt cylinder head side	0-3000 p.s.i.	2.53v-12.53v	P2	1
Pressure-Lift cylinder	0-3000 p.s.i.	2.47v-12.46	P3	2
Angle-θx (from x axis)	$(-45^{\circ})-(+45^{\circ})$	0v-5v	P4	3
Angle-θy (from y axis)	$(-45^{\circ})-(+45^{\circ})$	0v-5v	P5	4
Angle-θm (from vertical)	$(-45^{\circ})-(+45^{\circ})$	0v-5v	P6	5
Strain-(side moment)	$(-250\mu\sigma)-(+250\mu\sigma)$	0 ± 11.25mv	P7	6

statement. A/D output is 12 Bits (Full scale is represented by 4095_{10} $= FFF_{16}$.*)

Derivation of Analog Signal CALIBRATION FACTORS - Located in "CALBR" Table

(Engineering Units) Parameter Value = (A) * (A/D Output) + (B)

P1, P2, P3 (0-5v DC) = 0-3000 psi = $0\text{-}2.0685 \times 10^7$ N/m^2

A/D input: 0v = 000_{16}@A/D output or $(0)_{10}$

A/D input: 5v = FFF_{16}@A/D output or $(4095)_{10}$

$\therefore$ 5v = full scale = 2.0685×10^7 = FFF HEX or 4095 Decimal

CALIBRATION EQUATIONS FOR P_1, P_2, P_3:

1) $(4095) * (A) + B = 2.0685 \times 10^7$ N/m^2

2) $(0) * (A) + B = 0$ N/m^2

$\therefore B = 0$

Substituting: $(4095) * (A) + 0 = 2.0685 \times 10^7$

$$A = 2.0685 \times 10^7/4095 = 5051.28_{10}$$

P4, P5, P6 (0-5v DC) = (-)45 degrees to (+)45 degrees

1) $0 \cdot (A) + B = -45$

$\therefore B = -45$

2) $4095 \cdot (A) + B = 45$

$4095 \cdot (A) - 45 = 45$

$4095 \cdot (A) = 90$

$A = 90/4095 = 0.02197802_{10}$

P7 (0-5v DC) = (-) 250 μ strain to (+) 250 μ strain

1) $0 \cdot (A) + B = -250$ μ strain

*(A/D) output is in Hexadecimal format, but decimal values are shown.)

$\therefore B = -250$

2) $4095 \cdot (A) + B = +250$

$4095 \cdot (A) + (-250) = +250$

$4095 \cdot (A) = 500$

$\therefore A = \frac{500}{4095} = 0.12210012$

Signal Conditioning

The Signal Conditioning card transforms the input signal (from a transducer) to a 0-5 Volt output which is then fed to the A.D. converter for analog parameter measurement. The various transducer inputs are discussed in the preceeding paragraphs.

There are eight channels of conditioning circuitry, 2 are currently unused. The general architecture consists of two amplifiers in series for each channel. The first is connected in a standard differential configuration; the second stage provides gain and any offset required to obtain the 0-5v output. The amplifiers are LM324 single-supply quad op-amps.

CALIBRATION INPUT/OUTPUT PINS

TABLE E-2

Parameter		Input Pins (Edge Connector)	Output Pins (Edge Connector)	Signal Channel
$Press_T$ (rod)	P1	11, 13	12	1
$Press_T$ (head)	P2	15, 17	16	2
Press Lift	P3	21, 23	20	3
Angle - Θx	P4	27, 29	26	4
Angle - Θy	P5	33, 35	32	5
Angle - Θm	P6	39, 41	38	6
Strain	P7	45, 47	44	7

Analog Circuit Calibration Procedure

There are two steps in the calibration procedure. Insert signal conditioning card onto card extender to obtain access to trim pots, with power off. Then reapply power. Refer to circuit schematics in Appendix B.

1. Lower the carriage to the lowest position with the mast vertical. With the engine not operating, release the pressure in the hydraulic cylinders by cycling both the tilt and lift levers. Adjust the offset potentiometer for the respective channels as follows, with power on:

   a. P1, P2, P3:

   Connect the respective transducer to the input of the proper conditioning channel and adjust the potentiometer R5 for 0.0v at the output pin. Table E-2 lists the edge connector pins required. This is the offset "zeroing" adjustment.

   b. P4, P5, P6,

   Connect the respective transducer to the proper input channel (see Table E-2) and adjust potentiometer R5 for 2.5v at the output when the vehicle is under these conditions:

      1) Level surface ($\theta x = \theta y = 0$)

      2) Mast angle = 0 (vertical)

3) No side load

2. Remove power to the Monitor, and set the channel "full scale" outputs using an external d.c. power supply. The transducers should be disconnected, allowing the external voltage to simulate a full-scale analog signal for calibration purposes. Use the following values:

   a) P1, P2, P3 input = 12.5v, adjust R4 to obtain 5v output for the respective signal channel.

   b) P4, P5, P6 input = 5v, adjust R4 to obtain 5v output for the respective signal channel.

   c) Strain-Channel calibration P7--Proper calibration of the strain gage is achieved by the following procedure:

   1. Output offset adjust: Connect a voltmeter between TP-1 (card in slot 8B) and Analog ground. (Positive lead to TP-1) Connect a shorting jumper between rear panel terminal strip connection F3 and F4. This effectively "zeroes" the input to the strain conditioning. Adjust output offset trimpot R-3 to obtain a reading of 2.5 volts as indicated by the DVM. Remove jumper from F3 and F4.

   2. Bridge Balance Adjust: Connect voltmeter to rear panel terminal strip connections F3 and F4 (Polarity is of no consequence) Adjust Bridge Balance trimpot R-2 (card slot 8B) for an indication of 0.0 volts. Disconnect voltmeter.

   3. Gain Adjust: Strain Channel Gain Adjustment is accomplished by applying a known constant <u>side</u> load (tensile or compressive)

at a right angle to the mast at a known constant mast height (i.e., 200 lbs.@ mast height of 8 ft. measured from origin of reference system = 1600 ft. lb. f moment). This side-load is full scale strain on the corresponding side to which the transducer is mounted. Apply a side load of 200 lbs. to the vehicle at a mast height of 8 ft. Connect a voltmeter to TP-1 (slot 8-B) and to analog ground. Positive lead to TP-1. Adjust grain trimpot R-4 (slot 8B) for meter reading of 5.0V. Disconnect voltmeter.

3. The calibration of the A/D converter is essential to a properly functioning system.

Offset and full scale adjustments are accomplished by adjusting offset and gain of the Analog-to-Digital converter. Connect a voltage source to multiplexer channel zero, ground $\overline{\text{clear enable}}$ and load the address by momentarily grounding $\overline{\text{STROBE.}}$ After the voltage source has been addressed, set the voltage source to zero volts. Connect a triggering source and adjust the offset potentiometer until all output bits are logic zero with bit twelve dithering between logic zero and one. Change the source voltage to the most positive value of the input range minus one LSB. (1 LSB = 1.22 mv) Adjust the gain potentiometer until all output bits are logic one with bit twelve dithering between logic one and zero.

4. Altering Parameter Values

The geometric parameters stored in DMOS memory describe the

physical vehicle and are therefore unique to any given vehicle. Capability to alter these values for use of the Monitor on different Ford Trucks is essential. The list of constants and the specific procedure to alter them is discussed in Appendix D, operation.

APPENDIX F

VEHICLE CONSTANT

APPENDIX F

VEHICLE CONSTANT

The following discusses the determination of the constants which specify the vehicle geometry as required by the WFT STABILITY MONITOR. These constants are required in order to enter parameters as specified in Table 4-1.

In each case, the assigned parameter number and units are shown in this table.

Xv, Yv, Zv - Components of the Vehicle Center-of-Gravity.

Length (in meters) of X, Y, and Z components of the position of the center of gravity of the vehicle measured from the center of the area of contact of the left front tire (See Fig. F-1--Note: Yv is negative).

λ_{LRX}, λ_{LRY}, λ_{LRZ}, λ_{RRX}, λ_{RRY}, λ_{RRZ}--Direction Cosines of the Left and Right Roll Axes.

Each of these are direction cosines for describing the left and right roll axes. Calculate as follows: measure the component lengths of the position of the pivot point on the rear axle (X_5, Y_5, Z_5) relative to the center of the area of contact of the left front tire (note Y_5 is negative).

λ's are calculated as follows:

Wv - Weight of the Vehicle.

This is the weight force of the vehicle less the

Let $L = \sqrt{X_5^2 + Y_5^2 + Z_5^2}$

$\lambda_{LRX} = \frac{-X_5}{L}$ (negitive number)

$\lambda_{LRY} = \frac{-Y_5}{L}$ (positive number)

$\lambda_{LRZ} = \frac{-Z_5}{L}$ (negitive number)

$\lambda_{RRX} = -\lambda_{LRX}$ (positive number)

$\lambda_{RRY} = \lambda_{LRY}$ (positive number)

$\lambda_{RRZ} = \lambda_{LRZ}$ (negitive number)

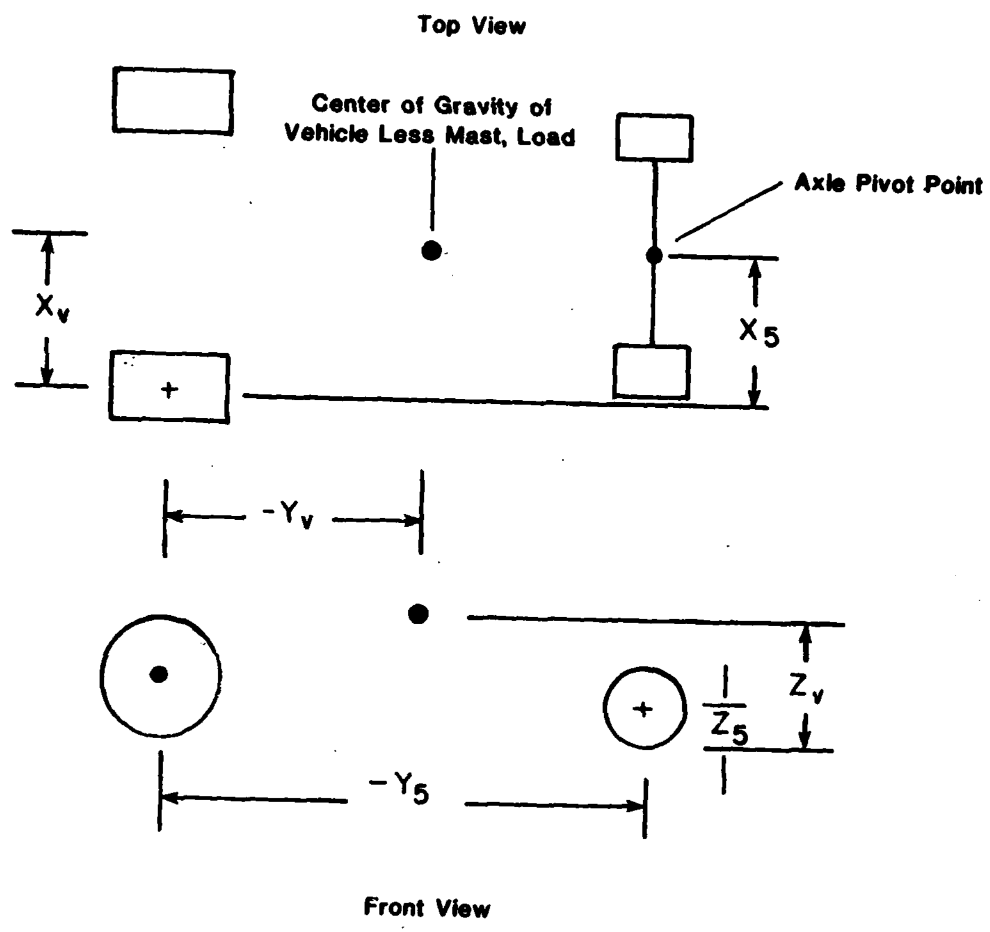


Figure F-1 Vehicle Geometry

mast and load. The weight force (mass times acceleration due to gravity) will be expressed in Newtons. Conversion factor is:

$$W \text{ (Newtons)} = 4.458\ W \text{ (Pounds Force)}$$

Wm - Weight of the Mast

The weight force (in Newtons) of the stationary portion of the mast. The stationary portion of the mast is defined to be that part which is not elevated by the lift cylinder.

P_{R2X} - Width of Front Tires.

Width of front tires measured in meters, from center-line to center-line.

Xm, Ym, Zm - Components of the Mast Position.

The mast is typically supported by the front axle at two different locations (adjacent to the two front tires). This is described as follows (refer to Fig. E-2).

$$Xm = Xm_1 + Xm_2$$

$$Ym = 0$$

$$Zm = 2 * Zm_1$$

X_T, Y_T, Z_T - Components of the Tilt Cylinder Position.

The tilt cylinders are attached to the vehicle. The points at which the tilt cylinder are attached to the vehicle are described as follows (refer to Fig. F-2).

$$X_T = Xm$$

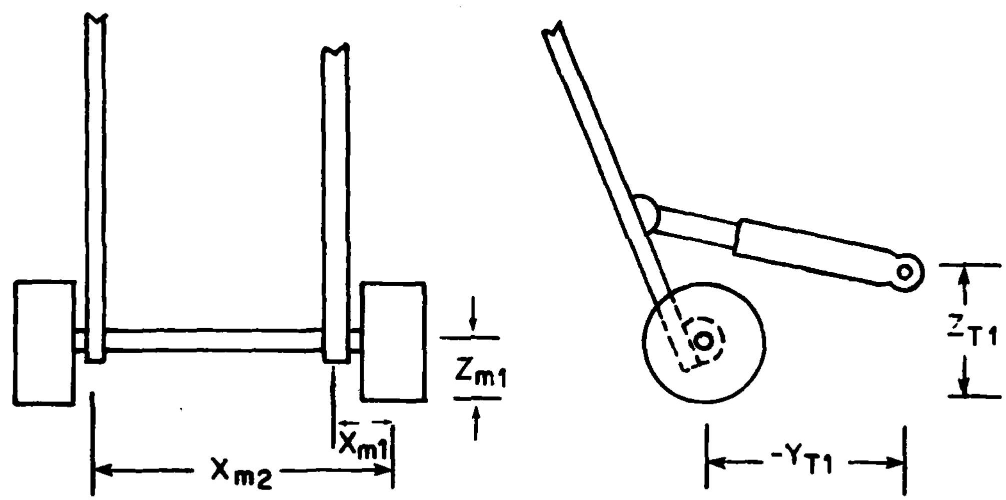


Figure F-2 Mast Geometry

$Y_T = 2 \cdot Y_{T1}$

$Z_T = 2 \cdot Z_{T1}$

A_1, A_2, A_{Lift} - Areas of Cylinders.

A_1 = Piston area on head side of a single tilt cylinder.

A_2 = Piston area on rod side of a single tilt cylinder.

A_{Lift} = Effective area of lift cylinder. For compound cylinder, this will typically be the area when the cylinder is at high elevations. This area should be altered by the chain multiplication factor (if appropriate). Thus, if a chain is used to multiply the lift cylinder force by a factor of two, the effective area should be doubled.

K - Strain Scale Factor.

Calibration constant which related strain observed in the mast upright to amount of side load. Specifies the amount of side load torque (in Newton-Meters) required to observe 1μ strain on the strain gauge.

The analog circuit has been calibrated for 5 volts equal ________ μ strain. This factor should be determined by the following procedure.

1. Calibrate strain gauge as discussed in Appendix E.
2. With mast vertical and fully elevated, apply a 445 Newton (100 pounds force) load to the forks pulling to the side.
3. Observe the measured strain (P7).
4. Calculate K

$$K = \frac{(100 \text{ Newton}) \quad (\text{Fork Height (M)}}{\mu\text{strain}}$$

$S_{p \text{ limit}}$, $S_{LR \text{ limit}}$, $S_{RR \text{ limit}}$

Limit for detecting instability, should be determined by experience.